

# **Ultra-Fast Portable Metallic/Concrete Plate Cutting**

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## **Abstract.**

The goal of this report is to develop and evaluate methods of ultra-high and high-rate cutting technologies for use in military and civilian realm. The information presented in this report reveals that defeating exposed rebars, steel reinforced concrete walls, steel encased concrete doors, and steel plate doors is within reach of current technologies. We did not analyze any exotic solutions but proposed to use or modify current technologies through clever engineering.

Oxyfuel unit including 0.5-gallon gasoline tank with cutting torch assembly and 8 small cylinders of oxygen represents a typical portable unit. The overall weight of the package is 140 lbs. A team of two men can transport this package. The capability of this package is cutting 400 rebars  $\frac{1}{2}$  inch thick or making a cut 180 inches long on a plate 2.64 inches thick.

A typical portable cutting unit based on thermal lance concept has an overall weight 20 lbs., this includes handle and burning bar (3lbs) and a small oxygen tank (16 lbs.). Oxygen consumption is typically 4 ft<sup>3</sup>/min. A small gas cylinder can support 4 min. of cutting activity. A small package containing 8 small cylinders (weight 140 lbs.) is capable of cutting 48 steel rods of diameter 2.94 inches. The same package can pierce in a 1.6 inch thick concrete plate 37 holes of diameter approximately 0.8 inch.

Purity of oxygen is extremely important for fast cutting. A detailed analysis revealed that an optimum purity of oxygen is 99.5%.

A simple analysis indicates that the "quantity of work" determining step is amount of oxygen available. Liquid oxygen is 800 times denser than gaseous oxygen. Evidently, liquid oxygen is the final solution. German technology of direct cutting with liquid oxygen will be modified for portable units in Phase II.

Several processes based on producing strong flow of oxygen on a spot, including pressure swing, water electrolysis and decomposition of solid chlorates will be engineered in Phase II; this report provided some data for design. Such units can be mounted on 4WD vehicles and would feature portability. They will also guarantee production of oxygen in a very flexible way at any place in the world.

Two new fuels were analyzed and recommended in this report. A suspension of ultrafine aluminum in gasoline will essentially improve the performance of oxyfuel cutter. A mixture of aluminum and molybdenum trioxide is a good fuel for the SHS cutter; the temperatures produced resulted in evaporation of alumina. Theoretical calculation results in adiabatic temperature rise 4,500°C.

## **I. Introduction**

The goal of this report is to develop and evaluate methods of ultra-high-rate and high-rate cutting technologies for use in the civilian and military realm.

In civilian applications metal powder cutting is frequently used in cutting, scarfing and lancing of oxidation resistant materials. In steel mills, powder metal cutting is used to scarf large, bloomed ingots, slabs, and billets. Powder scarfing is less expensive than grinding. Powder lancing permits rapid, effective piercing of many materials that are difficult to pierce with a standard oxygen lance. These include iron and steel containing inclusions, firebrick, cinder block, aluminum billets, and sand and metal incrustations inside large castings. Typical powder lancing applications include: i) removal of blast furnace bosh plates, ii) removal of large iron masses (salamanders) that are deposited at the base of blast furnace, iii) cleaning of furnace linings, iv) furnace tapping to remove slag, v) cleaning of soaking pits, vi) removal of ladle skulls, and vi) piercing holes in reinforced concrete walls and floors.

Underwater welding/cutting techniques are used primarily for the repair of offshore platforms, particularly after the normal 5-year inspection period. However, these techniques have also been useful during the installation of new offshore structures and undersea pipelines, the installation of hot taps, the repair of dock and harbor facilities, the modification of and addition to underwater structures, and the repair of nuclear facilities. Permanent and temporary repairs to holes in ship and barge hulls have been conducted. The hulls and pontoons of semi-submersible drill ships have also been repaired. Other examples of applications include cutting of ship sterns from castings, cutting reinforced concrete under water, underwater ship husbandry operations, and salvage and rescue missions.

An ultra-fast cutting process has direct application when incorporated into a torpedo nose. Such a configuration will allow penetration of a torpedo through the submarine outer hull, bringing the warhead closer to the pressure hull prior to detonation. This technology has a direct application to the Half-Length Heavyweight Torpedo development program. In addition, application of this technology to a future modification of the Lightweight Hybrid Torpedo would significantly increase its lethality against submarine threats. The system payoff results by providing undersea warhead concepts with enhanced lethality against submarine threats by reducing the standoff between the warhead and pressure hull of double-hulled submarine threat. Although the application of this technology will enhance the performance of a variety of warhead concepts, potential payoffs may lie in the fact that a less complex (therefore more reliable) warhead may be employed in the torpedo to achieve the same lethality as a complex warhead at

greater standoffs. In addition, by providing a more robust warhead per unit weight and volume, warhead volumes may be reduced and maintain current capability against the threat of submarine target spectrum. This reduced warhead volume can be used to provide space for enhancing other torpedo systems (i.e., propulsion or guidance and control) or results in a shorter, more maneuverable torpedo.

Since the 1970's, US Marine Corps and US Army have identified defeating urban walls as one of the most critical technology areas in military operations in urbanized terrain. In certain engagements it will be necessary for the Military Operations in Urban Terrain (MOUT) war fighter to breach concrete, steel, steel doors, and laminate ceramic barriers in an extremely short time. Current technology to breach a typical urban wall (8 in of concrete) requires warhead and explosive weights, which cannot be easily carried by a marine or infantryman. In general current breaching devices utilize high explosives, commonly in the form of linear or conical shaped charges, explosively thrown plates, or individually formed holes loaded with explosives. High-levels of blast and noise are produced as well as high-velocity fragments. These effects are detrimental to personnel safety. While explosively driven high speed "flying plate" impactors have the capability to clear concrete from the target they often leave a large amount of concrete reinforcing re-bar, which needs to be removed before ingress to the protected area can be achieved. In addition, there are often steel plates, steel doors, ceramic glass and laminate structures, which need to be defeated as the part of the target penetration process. There is requirement for a small, high speed thermal cutter that can be attached with one hand, such as using rifle barrel as an extender, to the re-bar from one side of the barrier. It should be capable of cutting re-bar up to 2 inches in caliber in less than 5 seconds.

The goal of this research activity is to evaluate, improve and develop ultra-fast cutting methods, which can be used by US Navy in repair operations, salvage and rescue missions as well as ultra-fast penetration of torpedoes through the submarine outer hull. Military Operations in Urban Terrain should benefit by having breaching technology capable of penetrating concrete walls reinforced by steel bars, steel plates, steel doors, ceramic glass and laminated structures. The improvement for a civilian sector is obvious from the list of applications mentioned above. The most important civilian application is a requirement of having very fast breaching, which is portable and users friendly, technology for dealing with transportation massive disasters (train derailment in Germany in June 98) or terrorist actions (Oklahoma City bombing).

The novel methods proposed here are based on:

- 1.increasing flame speed by using ultra-fine metallic powders
- 2.increasing flame temperature by solid oxidizers



3. generating fast surface reactions with the cut material
4. generating highly volatile combustion products
5. fast erosion/cutting caused by a metallic jet

## **II. Background, technical approach and anticipated benefits.**

### **II.1. Background**

Thermal cutting process differs from mechanical cutting in that the cutting action is initiated by chemical reaction (e.g., oxidation) or by melting. Oxygen cutting is accomplished through a chemical reaction, in which the preheated material is removed by rapid oxidation in a stream of pure oxygen. Typical oxygen cutting process is oxyfuel gas for special situations; chemical flux cutting and metal powder cutting have been developed. The last two methods are good for cutting oxidation resistant materials. Oxyfuel gas cutting includes a group of cutting processes that used controlled chemical reactions to remove preheated metal by rapid oxidation in a stream of pure oxygen. A fuel gas/oxygen flame heats the workpiece to ignition temperature, and the stream of pure oxygen feeds the cutting (oxidizing action). The oxyfuel gas cutting (OFC process) can cut low-alloy plate of virtually any thickness. The OFC process commonly cuts castings more than 30 in. thick.

The simplified oxyfuel gas cutting equipment consists of two cylinders (one for oxygen and one for the fuel gas), gas flow regulators and gages, gas supply hoses, and a cutting torch with a set of exchangeable cutting tips. Such manually operated equipment is portable and inexpensive. Metal powder cutting processes require a mean of introducing metallic powder in the cutting oxygen stream after the powder is conveyed to the cutting torch. A typical powder cutting equipment setup includes the following components to accomplish it: i) dispenser to supply powder during cutting ii) source of dry compressed air or nitrogen to convey the powder from dispenser to the cutting oxygen stream iii) powder nozzle or attachment to introduce the powder into the cutting oxygen stream iv) cutting torch to control the gases required to burn the oxygen/powder mixture.

With oxidation-resistant materials, such as stainless steel or concrete, either a chemical flux or metal powder is added to the oxygen stream to promote the exothermic reaction. High-alloy steels, stainless steels, cast iron, and nickel alloys do not readily oxidize and therefore do not provide enough heat for continuous reaction. These materials can be cut effectively by injecting metal powder (usually iron) into the oxygen jet. The metal powder supplies the combustion heat.

Chemical flux cutting process is well suited to materials that form refractory oxides. Finely pulverized flux is injected into the cutting oxygen stream before it

enters the cutting torch. The torch has separate ducts for oxygen preheating, fuel gas and cutting oxygen. When the flux strikes the refractory oxide (as e.g., in concrete  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{CaO}$  or oxides generated in situ from the stainless steel), it reacts with them to form a slag of lower melting temperature compounds. This slag is driven out, enabling the cutting process to proceed. Chemical fluxing methods are commonly used to cut the stainless steel.

Underwater OFC process uses a special torch, similar to a standard manual torch with an added passage for a stream of compressed air to shield the flame. The shield of compressed air also keeps water out of the cutting area. The depth at which underwater cutting can be used is of frequent concern. The only factor that differs under water is the increased heat loss to the surrounding medium.

## **II.2. Technical approach**

### **II.2.1. Model and physical process of cutting metals.**

One distinguishing feature of all cutting processes is the intensity of the heat source used to melt the solid material. Virtually every focused heat source can be applied to cutting. However, many of the characteristics of the cutting are determined by intensity. For example, when the heat flux is not high enough, the heat conductivity of the metal is able to remove the heat from the hot spot and no melting occurs. Eager [1] indicated that heat source power densities of approximately  $1000 \text{ W/cm}^2$  are necessary to melt most metals. At the other end of the power-density spectrum, heat-intensities  $10^6$ - $10^7 \text{ W/cm}^2$  will vaporize most metals within a few microseconds. Typical spectrum of heat fluxes produced by different methods is in Fig.1.

For a planar heat source on a steel surface an approximate formula can be developed, which correlates the heat flux,  $q$ , and time necessary to produce melting on the surface,  $t_m$  :

$$t_m \approx [5,000/q]^2 \quad (1)$$

The constant 5,000 is given by thermal diffusion in steel. Materials with higher thermal diffusivity will increase the time to produce melting by a factor of two to five.

If the time to melting is considered to be a characteristic interaction time, then a graph, see Fig.2, can be produced. Heat sources with power densities that are of the order of  $1000 \text{ W/cm}^2$ , such as an oxyacetylene flame, require an interaction time of 25 sec. with steel, whereas laser or electron beams at  $1 \text{ MW/cm}^2$  need an interaction time  $25 \mu\text{s}$ . Materials with high thermal diffusivity, such as copper or

aluminum, lie near the top of the band in Fig.2.; whereas steels, nickel alloys or titanium would lie in the middle. Ceramic materials with very low thermal diffusivity lie near the bottom of the band. Another important parameter for cutting is the relation of heat flux and the width of the heat-affected zone (HAZ); see Fig. 3. This can be calculated easily from solution of the transient equation for heat conduction. The HAZ is the zone adjacent to the cut, which did not melt. This zone will characterize the amount of heat wasted during the cutting process. From the material presented here it is evident that methods, which would result in a higher heat flux would also produce higher cutting speeds. Therefore, below you will find more details on methods of increasing the heat flux.

It is obvious that the heat transfer will essentially effect the cutting process. The heat flow and fluid flow in the weld pool can significantly influence the pool geometry, the temperature gradients and the local cooling rates. Recent studies have demonstrated that in most cases the fluid flow and the heat transfer in the weld pool are controlled by the spatial variation of surface tension that exists on the weld pool surface. The spatial variation of surface tension causes the molten metal to be drawn along the surface from the region of higher surface tension to that of lower surface tension and this may result in very large surface flows and thus excellent heat transfer in the pool. The surface tension is highest near the solid-liquid interface causing the flow to be outward and away from the center of the pool [2]. Metals in the liquid state feature much lower viscosity than liquid oxides contained in liquid concrete. Liquid concrete has very high viscosity close to melting point and very strong overheating of this lava is necessary to blow off the produced liquid oxides. Owing to the very high viscosity of the molten pool of lava the heat transfer in the concrete liquid is very low and cutting concrete is much more difficult task compared to cutting metals.

### **II.2.2.Combustion of suspension of solid metallic particles in gases.**

Combustion of a suspension of solid metallic particles in a gaseous oxidizing medium (premixed and diffusion dust flames) is very important for the problem of fast cutting. Unfortunately, the understanding of dust combustion phenomena is still in a rudimentary state compared to gas flames. This is mostly due to the lack of reliable fundamental data on burning velocities in metallic dust combustion. With the exception of coal dust flames very limited data are available in the literature on the combustion other dusts, in particular metals.

Cassel [3] in his pioneering work measured burning velocities in aluminum-air suspensions using a Bunsen type burner. He worked with lean dust mixtures and the dust concentration was relatively narrow: between  $B = 120-150 \text{ g/m}^3$  and 270-

300 g/m<sup>3</sup>. The stoichiometric fuel concentration in aluminum-air suspensions is about 305 g/m<sup>3</sup>. He found that for atomized aluminum dust with a particle size 5-10 $\mu$  the burning velocity increases with the dust concentration from 20-25 cm/sec. near the lean limit to about 40 cm/sec. for dust concentrations close to stoichiometric. Cassel also found that the burning velocity for lean mixtures increases approximately as  $\sqrt{Y}$  when the oxygen content, Y, in the O<sub>2</sub>-N<sub>2</sub> mixture increased from 21% to 100% of oxygen. The experimental data indicated that the burning rate levels off in a wide range of dust concentrations after the maximum was reached. Recently, detailed data on combustion of aluminum dust in oxygen were obtained by Goroshin et al. [4]. The burning velocities in a rich aluminum dust cloud ( $d_p = 5.4\mu$ ) were measured in a Bunsen type pre-mixed flame by determining of the surface area of the inner flame cone and the total volumetric flow rate. It was found that in rich Al-O<sub>2</sub>-N<sub>2</sub> mixtures the burning velocity is a very weak function of dust concentration.

The results of measurements of burning velocity as a function of dust concentration in mixtures of nitrogen with different oxygen content are shown in Fig.4. In general, the minimum dust concentration in which the stabilized flame can be observed (i.e. stability limit), increases with decreasing oxygen concentration of the mixture. The absence of experimental points at low dust concentrations for the mixture with the highest initial oxygen content (30% O<sub>2</sub>) can be explained by the fact that at low dust concentrations this flame has a strong tendency toward a flashback. As can be seen from Fig.4, the value of mass concentration of fuel in rich mixtures does not effect the flame speed for the whole range of investigated dust concentrations.

The inert gas (nitrogen) can be replaced by argon or helium to investigate the role of the gas molecular transport properties such as the thermal heat conductivity a (cm<sup>2</sup>/sec.) and oxygen diffusivity D (cm<sup>2</sup>/sec.) Direct interferometric measurement demonstrated the negligible role played by radiation heat transfer in a small scale Bunsen type aluminum dust flame. For flames whose propagation velocities are controlled by the molecular heat transfer, the burning velocity, v, (cm/sec.) depends on thermal heat conductivity and the characteristic time of the chemical reaction,  $\tau_c$ , (sec.) as

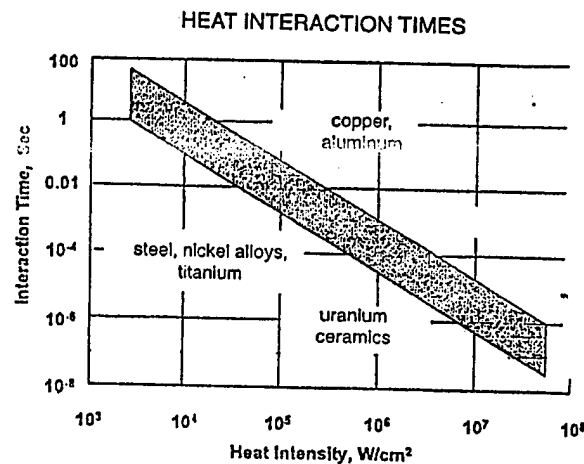
$$v \approx \{a/\tau_c\}^{0.5} \quad (2)$$

Our experience indicates that a particle with a diameter of approximately 5 $\mu$  is controlled by the process of oxygen diffusion towards the particle surface and thus characteristic combustion time is inversely proportional to the oxygen diffusivity;

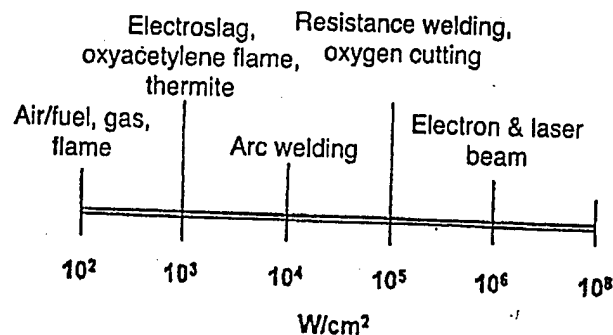
$$\tau_c \approx 1/D \quad \text{and therefore} \quad v \approx \{aD\}^{0.5} \quad (3)$$

This means that the flame speeds in argon and helium mixtures should be related as

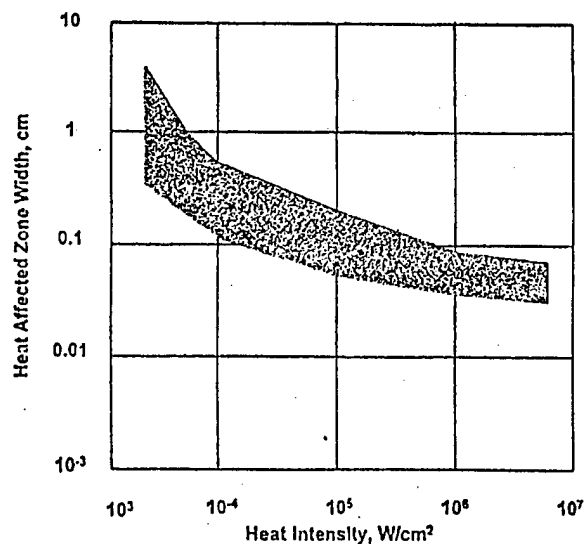
$$v_{He}/v_{Ar} = \{(aD)_{He}/(aD)_{Ar}\}^{0.5} \quad (4)$$



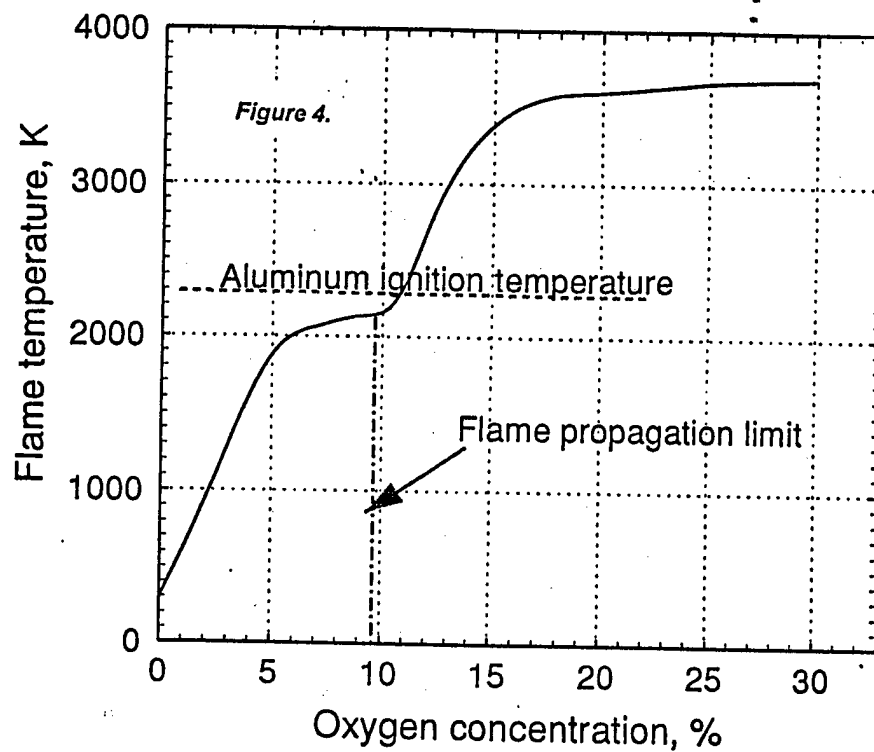
**Figure 1.** Typical weld pool-heat source interaction times as function of heat-source intensity. Materials with a high thermal diffusivity, such as copper or aluminum, would lie near the top of this band, whereas steels, nickel alloys, or titanium would lie in the middle. Uranium and ceramics, with very low thermal diffusivities, would lie near the bottom of the band.



**Figure 2.** Spectrum of practical heat intensities used for fusion welding



**Figure 3.** Range of weld HAZ widths as function of heat-source intensity



taking into account identical flame temperatures in both mixtures. Equation (4) predicts that the flame speed with helium should be about 3.9 times higher than that with argon. Experimental information shows only a 3.2 times difference.

There are only few data in the literature on the flame front velocity in systems containing iron powder. Aslamov et al. [9] measured front velocity for iron powder with  $d_p = 4.9\mu$ . The concentration of the suspension was 150-400 g/m<sup>3</sup>. A typical front velocity was 0.1 m/sec. Evidently, the front velocity is approximately 50% of that measured for aluminum powder.

For particles, which are in the sub-micron range the characteristic time for the chemical reaction cannot be replaced by  $1/D$  and much higher velocities of flame propagation result. Such data are completely missing in the literature since so far large-scale production of sub-micron aluminum or iron was not developed.

### 2.2.3. Use of fine powders.

All experimental data currently reported in literature have been based on the finest particles of aluminum or iron, which have been prepared via the atomization route. Such a technology does not make it possible to manufacture metallic powders with diameters  $d_p < 5\mu$ . Such a powder features a surface area of  $S = 0.1-0.2$  m<sup>2</sup>/g. A proprietary technology developed by Ceramic and Materials Processing Company makes it possible to manufacture powders of both iron and aluminum, which is sub-micron with the surface area of 5-35 m<sup>2</sup>/g. An in-house experience reveals that these powders do not react in a diffusion regime but burn extremely fast. However, to get a very pessimistic estimate we can assume a diffusion regime of combustion. If we rewrite Eq.(3) as

$$\tau_c \approx 1/S \quad (5)$$

then the simple calculation reveals that the flame propagation for a powder with  $S = 1.0$  m<sup>2</sup>/g is ten times higher than that for  $S = 0.1$  m<sup>2</sup>/g. Since the flame speed represents the heat flux to the solid surface we can expect cutting velocity by one order of magnitude higher compared to the cutting speed produced by commercially available micron powders.

An interesting modification of currently used cutting torches would be a new fuel developed by Ceramics and Materials Processing Company. This fuel is a slurry of ultra-fine aluminum with surface area  $S > 35$  m<sup>2</sup>/g in a light hydrocarbon. Evidently this slurry can be used in a standard (or slightly modified) OFC process. We can expect the velocity of propagation of this flame extremely high. To our best knowledge information about such a system is completely missing in the literature. In future we are contemplating for this research to prepare via our generic method also a slurry of ultra-fine titanium with a stoichiometric mixture of

boron powder. It is known that such system is producing reaction temperatures in the range of  $3500^{\circ}\text{C}$ .

Several other slurries in light hydrocarbons are possible. For example, slurry of ultra-fine aluminum powder and molybdenum oxide,  $\text{MoO}_3$ . It is known that in a dry mixture of these powders the flame speed is 150-600 m/sec, see Reference [5]. This slurry can be also prepared by the techniques developed in Ceramic and Materials Processing Company. Information about flame propagation speed in slurry is not known.

#### **II.2.4. Use of new type of oxidizers.**

In the currently used OFC process or metal powder cutting technique oxidizer is provided as a stream of gaseous oxygen. The oxygen in a gaseous form is stored in high-pressure gas cylinders. Liquid oxygen has been recommended and used for large jobs because the cost is much lower for the same amount of oxygen when it comes as a liquid vs. a compressed gas, and the cylinder time is greatly reduced. However, for the high-performance cutting job a solid source of oxygen can be used. A best source of solid oxygen is iodine pentoxide,  $\text{I}_2\text{O}_5$ . According to published thermodynamic data [6] the reaction between aluminum and iodine pentoxide produces  $(-\Delta H) = 1486 \text{ cal/g}$  or  $(-\Delta H) = 6122 \text{ cal/cm}^3$ . This compares favorably with the exothermic reaction between Al and  $\text{MoO}_3$ , which is producing the values 1124 and 4279, respectively. The important issue for the former reaction is the fact that the reaction products are completely in the gaseous phase with 0.6293 moles/100g, which corresponds to approximately 153 liters/100g of gas at the reaction temperature. Iodine pentoxide is a stable compound, which can be manufactured easily on a large scale. Experiments carried by us indicated that iodine is released during the combustion process and the cloud of iodine makes it difficult for the operator to work without a gas mask.

Another effective source of solid oxygen can be lithium peroxide,  $\text{Li}_2\text{O}_2$ . Unlike other peroxides,  $\text{Li}_2\text{O}_2$  is a stable compound, which can be decomposed only at higher temperatures. Data on oxidation of metals both by iodine pentoxide and lithium peroxide is missing in the literature. Both solid sources of oxygen can be injected by a gaseous oxygen stream to the torch; this modification would guarantee large excess of oxygen at the hot metal-gas interface.

Using oxygen for cutting of steel plates is associated with the problem of generating oxides which will never be converted to gaseous products and it is necessary to blow them away from the cut by a strong stream of gas. However chlorides or fluorides are very volatile and this problem would be eliminated. Therefore, for effective cutting different oxidizers should be considered. Since it is



difficult to work with halogens it is possible to replace them by a convenient source of perchlorinated or perfluorinated compounds. Typically as a source of chlorine we have proposed hexachlorocyclohexane or tetrachlormethane; and as a source of fluorine we can use a Teflon powder. Both oxidizers produce a large amount of heat and generate a very fast flame. We are not aware of any literature data on the chlorine-metal flame; however, we have information of metal-fluorine flame. Martin and Murray reported [5] that aluminum and Teflon will produce energy of  $4,650 \text{ cal/cm}^3$  or  $2,100 \text{ cal/g}$ . The velocity of the propagating flame depends on the particle size of aluminum and for ultra-fine sub-micron particles can reach value  $100\text{-}800 \text{ m/sec}$ . Russian scientists reported that for systems "Al-fluorine polymer-oxygen" the velocity of the flame front increased by factor 2.1-2.3 compared to systems without fluorine; see Yagodnikov et al. [7].

Finally, for special type of operations, if ultra-fast cutting is the necessity an application of halogen fluorides should be considered. These fluids are extremely active chemically, when brought into contact with most metals. They react violently with the generation of extremely high temperatures sufficient to melt, cut or burn the metallic object[8]. Examples of such fluids are chlorine trifluoride, chlorine monofluoride, bromine trifluoride, bromine pentafluoride, iodine pentafluoride and iodine hexafluoride and their mixtures. Application of these systems is known in drilling well industry. From the source [8] we learn that for cutting 3.5 inch drill pipe we need 1,020 g of  $\text{ClF}_3$  or 1,400  $\text{BrF}_3$ . For  $\frac{3}{4}$  inch tubing these value are 245 and 340, respectively. All the halogen fluorides react violently with water and, therefore, cannot be used for underwater cutting. However, for special type of salvage or rescue operations they may represent an ideal solution.

#### **II.2.5. Cutting by liquid oxygen.**

Combustion of massive metallic plates in air was almost completely neglected in the literature. The problem appears occasionally during certain fires, however, systematic attention was not paid to this problem. Combustion of massive aluminum metal plates plays an important role in cryogenic engineering; liquid oxygen is exchanging heat in the liquefaction process in the aluminum heat exchangers. In certain isolated cases spontaneous combustion of the heat exchanger was observed. Combustion of titanium plates is important in aerospace engineering, see References (10,11,13). There is very limited information on combustion of metallic iron or steel plates in oxygen. Kuo (14) observed a spontaneous ignition of steel plate in oxygen at higher pressure. Evidently, the first stage of ignition is a local melting of the metal, which is followed by a liquid-gas

reaction. The literature on reaction between liquid iron and oxygen is voluminous; namely this reaction is called Bessemer process in metallurgy. However, nobody tried in the past to transfer the information on Bessemer process to combustion of solid lump of iron in stream of pure gaseous oxygen or in liquid oxygen.

The author of this report observed a simultaneous combustion of tantalum powder in liquid nitrogen, see reference (15). Obviously, the reaction between liquid oxygen can occur in a combustion regime, however, was not studied so far. Preliminary experiments conducted by us revealed that large overheating is necessary to ignite a large metallic body (see below).

#### **II.2.6. Fast erosion by metallic jet**

Rozner (16,17) described a batch-operating device for fast cutting of metallic objects. His idea was to produce by aluminothermic SHS operation a jet of molten metal, which will impinge on a metallic object. The impingement of the liquid jet from the torch erodes the metal target within a distance up to 10 cm from the nozzle exit. When the jet strikes a target at high velocity, shock waves are introduced into the target body and the stress generated by the impact is higher than the yield stress of the target material (18,19). In this case, the jet is forcing itself into a target; a shallow crater is formed which expands rapidly as material is pushed aside. The expanding crater follows behind the initial impact shock wave, which is attenuated as it travels into the bulk of the target.

The torch contains solid pyrotechnic material made from different combinations of metal and metal oxide thermite mixtures that react exothermally. Reactive metals are represented by aluminum or titanium, as metal oxide Rozner used ferrous oxide ( $\text{Fe}_3\text{O}_4$ ), cupric oxide ( $\text{CuO}$ ), or cobalt oxide ( $\text{Co}_3\text{O}_4$ ). The pyrotechnic material contains also a small amount of Teflon, which serves mainly as a gas source but acts also as binder to increase the "green" strength of the pressed powder pellets. The torch consists of a cylindrical casing made out of mild steel, pyrotechnic charge, a nozzle, an igniter and a front closure arrangement. The torch casing must be capable of withstanding a peak pressure up to 1,000 atm. for about 1.0 second. The cutting performance of the torch depends to a large extent on the nozzle material and geometry. Large diameter shallow craters were cut in steel plates by torches with a single-hole nozzle. The deepest experimental perforation was achieved with torches containing multiple-hole nozzles. Nozzle erosion is detrimental to torch effectiveness because it substantially decreases the jet velocity, particularly during the latter stages of the cutting operation.

Torches 4.5 cm in diameter, 18 cm long were successfully used to perforate 2.5 cm thick steel plate and to severance of steel cables up to 2.5 cm in diameter. Larger

torches, 9 cm in diameter, 20 cm long were used to perforate 6 cm thick steel plate. A similar torch demonstrated the capability to cut through 5 cm diameter steel cable at an underwater depth 200-400 m. These perforations can be achieved in one second. Since this torch does not require the external support of oxygen, it is effective in both air and underwater environments. It can also be effective in outer space.

This torch is very similar in construction and performance with the cutting device developed by Gotzmer (22) for ultra-fast cutting of steel plates.

If  $v$  is the velocity of the combustion front [cm/sec],  $S$  is the cross-section of the combustor [cm<sup>2</sup>],  $S_1$  is the cross-section of the cutting nozzle [cm<sup>2</sup>],  $\rho$  is average density of the composite fuel [g/cm<sup>3</sup>],  $M$  is the average molecular weight of the solid-solid fuel,  $q$  is the heat flux [cal/cm<sup>2</sup>] and  $(-\Delta H)$  is the heat released by the exothermic reaction [kcal/mol] than the total thermal energy released by the exothermic reaction,  $h$ , and heat flux,  $q$ , are:

$$h = \{v\rho S(-\Delta H)\}/M \quad \text{and} \quad q = h/S_1 = v\rho(-\Delta H)/M \quad (6)$$

For a commercially available powders the heat flux  $q$  can be of the order  $q = 10^3 - 10^4$  W/cm<sup>2</sup>. For ultra-fine powders manufactured by Ceramic and Materials Processing Company these speeds can go to  $10^6 - 10^8$  W/cm<sup>2</sup>, which will guarantee the cutting of the hull of the submarine in time of the order of a millisecond.

Recent experiments carried out by Gotzmer (22) revealed that even with the aluminothermic mixture (particle diameter of Al  $d_p = 5\mu$ ) the heat flux can be  $10^6$  W/cm<sup>2</sup> and the penetration rate of the order of 30 milliseconds.

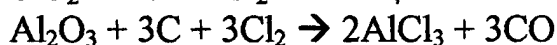
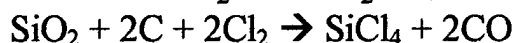
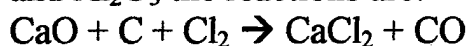
Using of SHS torch is justified for extremely fast cutting and for operations associated with cutting submarines hull. Our experiments revealed that in terms of flexibility and portability it cannot compete with oxyfuel torch or lance operated by a skilful operator.

#### II.2.7. Cutting of concrete and steel reinforced concrete.

This is very difficult problem to solve. Currently with concrete an oxyfuel-cutting torch is used with chemical flux and metal Fe powder added to the oxygen stream to promote the exothermic reaction. When the flux strikes the refractory oxides (as e.g., in concrete SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and CaO) it reacts with them to form a slag of lower melting temperature compounds. This slag is driven out, enabling cutting process to proceed. Our own observations revealed that this is a very difficult problem (23) and a new approach must be proposed to improve the oxyfuel cutting technology. The major obstacle in cutting is the very high melting point of oxides contained in a concrete material and their very high viscosity once they are in the liquid state. The high viscosity eliminates good convection in the pool of liquid and therefore a

low heat transfer results. As a result the environment dissipates the heat provided by torch and only a small fraction is used for melting of oxides. A new concept is necessary to cope effectively with this problem.

The concept we have proposed here is based on the idea of converting oxides contained in concrete to volatile chlorides. The idea is based on so-called carbo-chlorination reaction. For the major components contained in concrete, CaO, SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> the reactions are:



The products of these reactions are very volatile, boiling points of SiCl<sub>4</sub>, AlCl<sub>3</sub> and CaCl<sub>2</sub> are 57.6°C, 183°C and 1600°C, respectively. Melting point of calcium chloride is 772°C.

Carbon and chlorine necessary for the reaction can be generated in situ by the thermal decomposition of perchlorinated hydrocarbons. To achieve the goal of fast cutting an oxyfuel torch can be used; the fuel gas stream will contain a certain amount of perchlorinated hydrocarbon and the oxygen stream will contain potassium perchlorate, KClO<sub>4</sub>. The solid oxidizer provides excess of oxygen for the reaction and is reduced to KCl. Potassium chloride produces an eutectic mixture with calcium chloride with the melting point approximately 400°C, which can be easily blown off. If the flame hits a steel or iron reinforcing bar a large excess of oxygen will contribute towards a fast cutting.

This technology appeared as a very promising approach to attack reinforced concrete. Ceramics and Materials Processing Company has five years experience with carbochlorination reactions (24). Experiments revealed that certain chlorinated hydrocarbons have a tendency to extinguish the flame and they can be used only in low concentrations (below 7%). The produced "lava" exhibited completely different properties and can be easily removed from the cutting spot mechanically, see our research observations below.

#### **II.2.8. Batch and continuous operations and portability of the device.**

The operations described in this proposal represent both continuous and batch processes. The modified oxyfuel cutting device is representing a typical continuous process, which can operate for tens of minutes. On the other hand the SHS cutter is representing a batch process, which is over in times ranging from few seconds to several milliseconds. The cutting rate is dependent on the heat flux intensity which can range from 10<sup>3</sup>-10<sup>4</sup> W/cm<sup>2</sup> for oxyfuel cutters to 10<sup>6</sup> W/cm<sup>2</sup> for SHS cutters. The portability is an important issue. It is obvious that for fast and ultra-fast cutting

a large amount of fuel must be burnt in a very short time to produce the necessary heat flux. For instance, for the SHS cutter 800 g of pyrotechnic mixture must be used to perforate 6 cm thick steel plate. Such a torch will have 9 cm in diameter and 20 cm in length. A typical pressure inside the torch will be 200 atm.; the casing weight can be estimated to be around 8-10kg. An infantryman cannot carry more than 2 torches for an action. We are contemplating high-performance graphite for the next generation of torch casings. A good quality high-performance graphite, which is used to construct dies in high-pressing operation does not show any creep at temperatures 2500°C and the strength is better than steel. For more rigidity the graphite core can be encased by a very thin metallic sheet. The high-performance graphite torch can reduce the weight by factor 3; consequently an infantryman can carry 5-6 torches for an action. Big cutters, which are supposed to be used for cutting of massive steel doors must be transported to the cutting spot on wheels.

The important task of this proposal will be an effort of scaling-down of all reactors (flames, burners, cutters, etc.) so that pocket size units can be designed, constructed and operated (12).

### **III. Experimental Observations**

#### **III.1. Cutting Torch Products and Manufacturers**

Intensive search has been made through the Internet and Thomas Register. Manufacturers were located and detail information about their products has been collected. There are four types of cutting torches commercially available :

- **Oxy-Gasoline Cutting Torch:** Petrogen is the only manufacturer making the torch, which uses liquid fuel (gasoline). We have purchased the torch and modified it for purposes of portable units. The reaction between gaseous oxygen and gasoline generates temperature high enough to carry out even the toughest jobs. The fuel container used is a 2.5-gallon tank, which can be carried by the operator. Detailed description and experience with this type of technology is analyzed below.
- **Oxylance Cutting Torch:** A complete oxylance cutting torch package consists of a holder, a burning bar, an oxygen hose, a high volume oxygen regulator, an ignition system, and an oxygen cylinder. With oxygen flowing through the burning bar, which is mainly made of iron, the burning temperature is claimed as high as 10,000°F by the manufacturer. The flame perforates steel work-

piece by melting and burning it. Burning bars of 3/8"(D)x36"(L) and 1/2"(D)x48"(L) have oxygen consumption values of 9 cubic feet and 20 cubic feet respectively for each bar (data from **BROCO Company**, other companies have different data). It cuts steel easily. For concrete material, the best technology of producing a cut is to produce several holes on the concrete plate and then knock out the area. A hole on a concrete plate of thickness 2-4" can be made in between 30 seconds to 1 minute.

Many Oxy-lance manufacturers can be found. The selected companies are **BROCO, ARCAIR, P.G.E., Inc, Magnum, Oxylance Corporation, and PAASO. BROCO** seems to be the leading manufacturer in the group.

- **Powder Cutting Torch:** The following two companies were found:  
**Steel Industry Products** makes AC-4 Powder Cutting Torch System, which is capable of cutting 10" stainless steel. The torch is similar to a standard oxy-fuel torch, which uses propane/acetylene and oxygen. However, an aluminum/iron powder blend is usually used to enhance the heat output. The powder mixture flows through this torch and comes out around the nozzle and burns. The torch is able to sever concrete by using an aluminum/iron powder blend mixed at 10%-30% by volume. Particle sizes of the iron powder are in the range of -325 mesh to +100 mesh. Powder mixture is stored in a powder dispenser with N<sub>2</sub> as protection and transport gas. This set of equipment is expensive (about \$7,000) and is big and heavy.  
**Maintenance Welding Alloys** produces Flame Spray Powder Torch. Its applications includes repairing damaged metallic parts or surface treatment. The powders supplied by the company are made of nickel/chrome.
- **Plasma Torch:** **C&G Systems, Inc.** is one of the producers. However, this kind of torch is not applicable to our case since it cannot be easily modified to portable small units.

### **III.2. Cutting Data by Using Oxygasoline Cutting Torch**

This torch uses liquid fuel (gasoline) and oxygen. In our experiments tips #1 (recommended for cutting 1/4"-1" thick steel), #4 (recommended for cutting 4"-6" thick steel), and #6 (recommended for cutting 8"-10" thick steel) have been used. The higher the number the higher cutting power of the tip and the higher consumption of oxygen and gasoline. The fuel tank has a volume of 2.5 gallons and can be scaled down easily. Our experiments proved that the torch cuts steel

very fast and it can also melt or penetrate concrete. Since the oxygen supplying system can be scaled-down, this torch represents a powerful technology, which can be modified for portable and small units..

### **III.2.1. Cutting iron material.**

12 steel pieces of different shapes and dimensions were cut by using oxygasoline torch. Quantitative data were obtained from our experiments. Photographs of the workpieces before and after cutting are shown in Figures 1.1 to 1.12. Unleaded gasoline (octane number 93) was used as the fuel. The oxygen used was of industrial grade (99.5% O<sub>2</sub>). Two cutting tips were utilized for the experiments. For thick steel pieces, #4 tip was used and the oxygen and fuel pressures were 50 psi and 20 psi. For thin steel pieces, #1 tip was employed and the oxygen and fuel pressures were 25 psi and 20psi. The shape of the workpiece, cutting length, thickness, and cutting time were recorded in the attached figures. Pieces cut by #1 tip are marked in figures; the unmarked ones were cut by #4 tip.

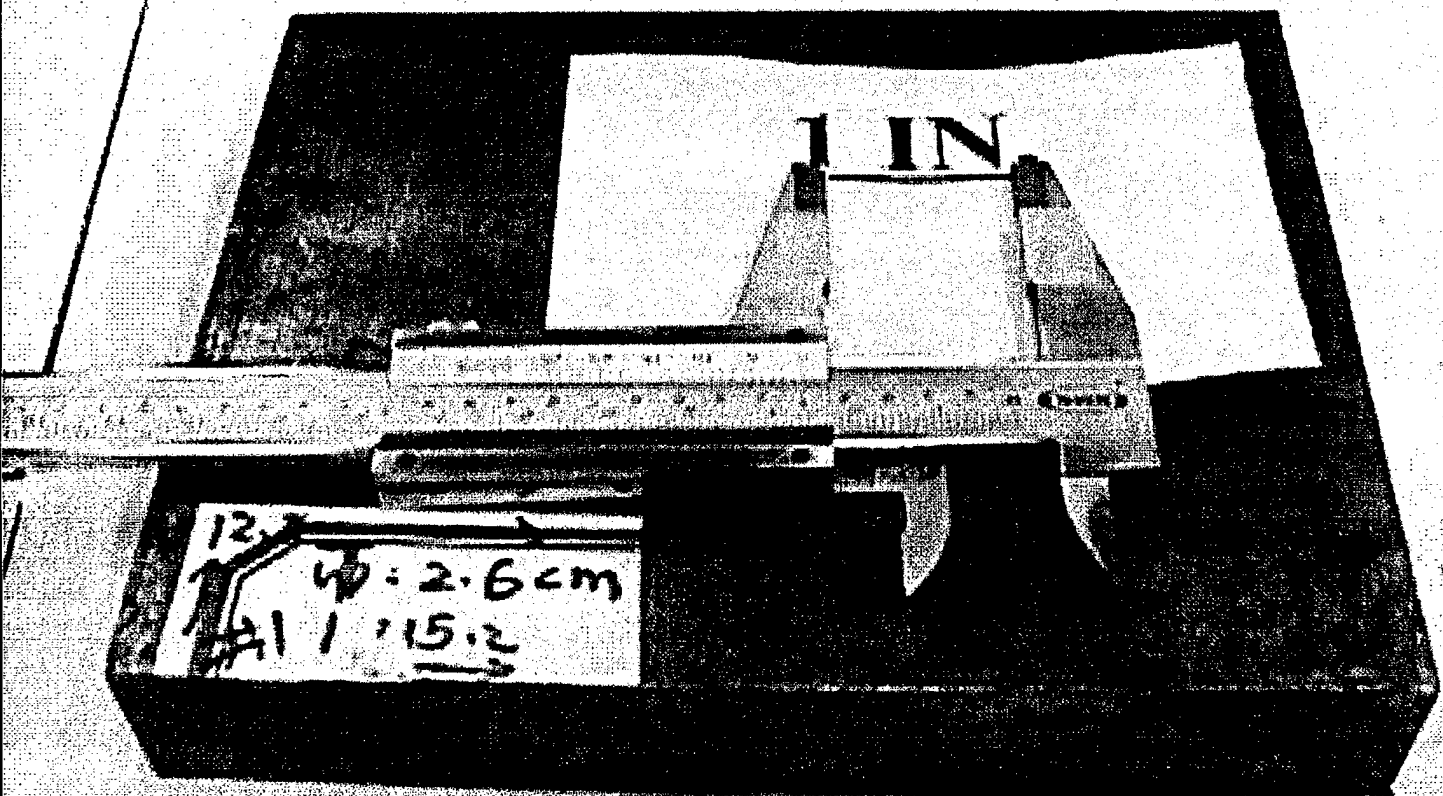
Oxygen consumption depends on the tip size, pressure of oxygen, and skill and ability of the operator. The average oxygen consumption for #1 tip at pressure=20 psi is 115 cf<sup>3</sup>/hour; for the tip #4 at pressure=50 psi the consumption is 370 cf<sup>3</sup>/hour.

The individual phases of the cutting process are displayed in Figures 1.14–1.19.

### **III.2.2. Cutting concrete**

The cutting of concrete, using Oxygasoline torch, was also tested. According to manufacturer data concrete can be penetrated by the torch. In our experiments #4 tip was used. Oxygen pressure was set to 50 psi and gasoline 20 psi. We were surprised that the torch is capable of melting the concrete piece. However, the molten lava did not fly easily out of the pool. Experiments also revealed that strong overheating of the holder takes place and apparently the long operation of cutting can damage the cutting unit. A hole can be penetrated on a concrete piece of thickness=14 mm in 57 seconds. A photo of the concrete piece after cutting is shown in Fig.1.13. Our experiments demonstrated that Oxygasoline torch alone is not well suited to perform this task and in future must be supported by simultaneous injection of metallic powders. All commercially available units are too clumsy and voluminous; in future we want to use aluminum powder slurry in gasoline to increase the energy output.

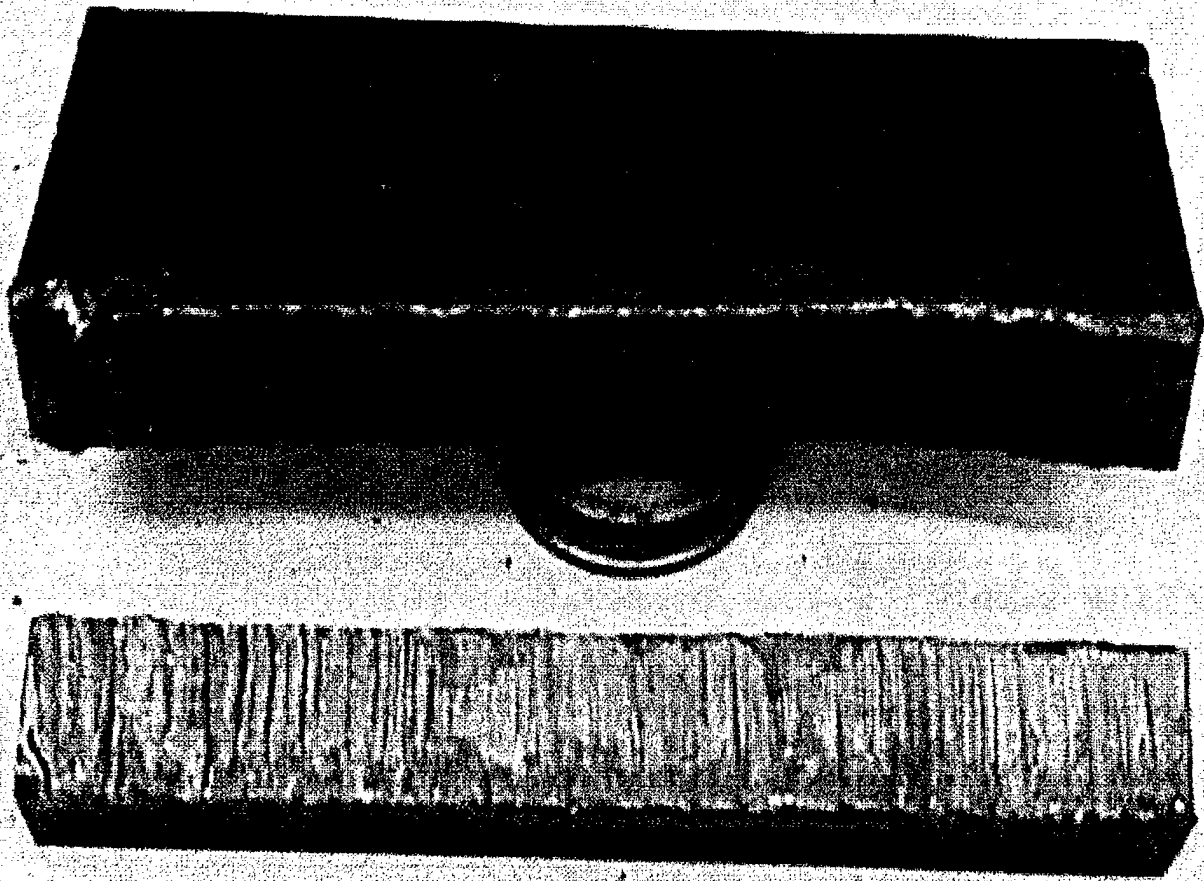
**5.98 IN x 5.04 IN x 1.02 IN**



**Fig.1-1a: Steel#1, Before Cutting**

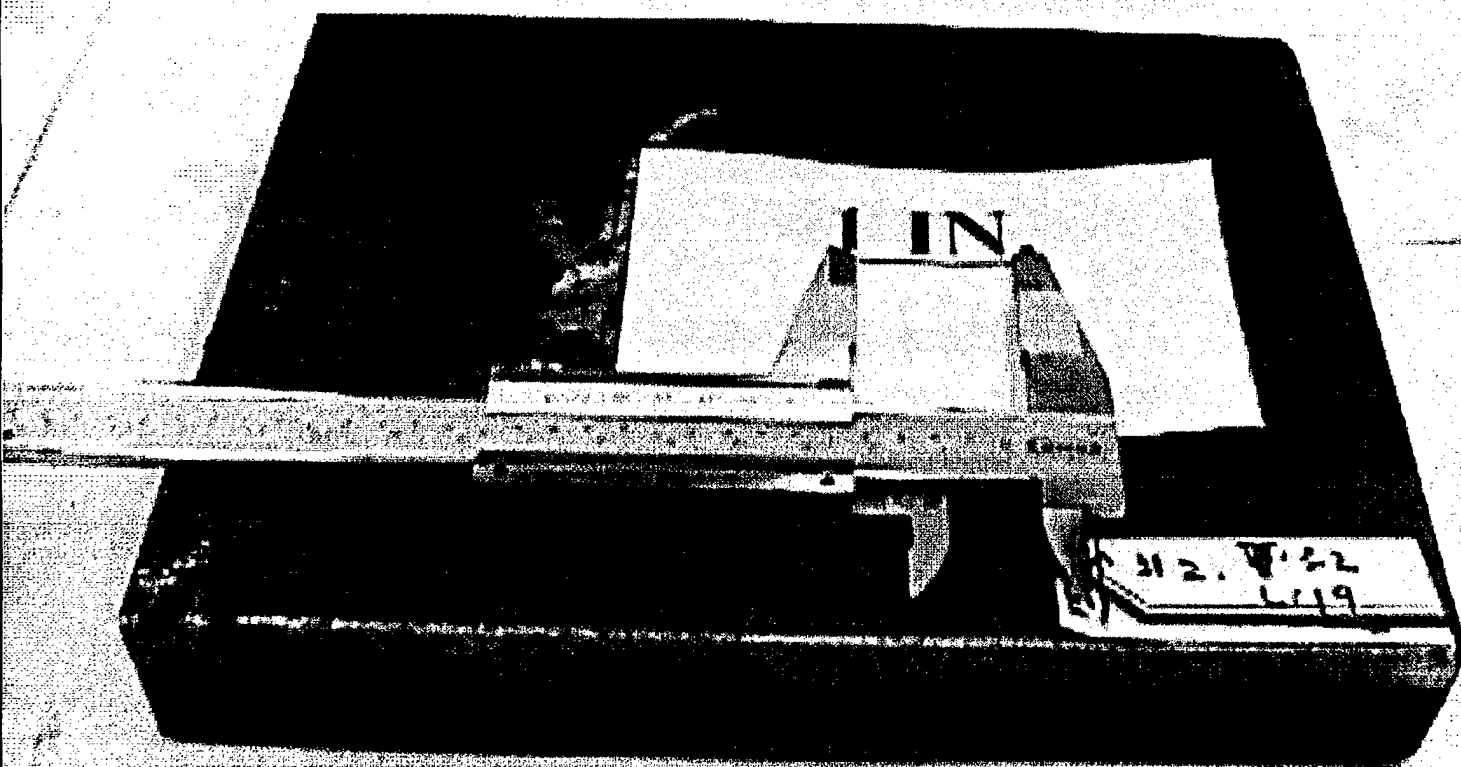


**Cutting Length = 5.98 IN, Time= 22 s**



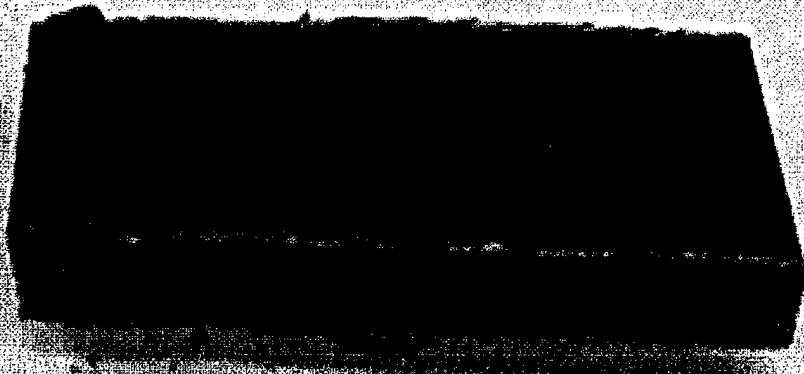
**Fig.1-1b: Steel #1, After Cutting**

**7.48 IN x 5.94 IN x 1.26 IN**



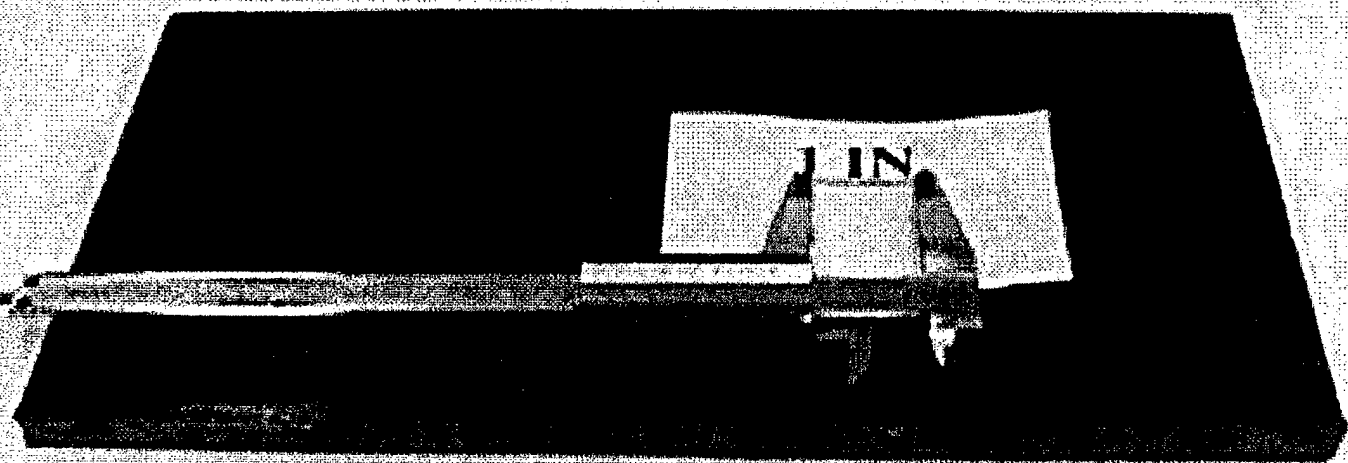
**Fig.1-2a: Steel#2, Before Cutting**

**Cutting Length = 7.48 IN, Time= 29 s**



**Fig.1-2b: Steel #2, After Cutting**

**11.81 IN x 6.42 IN x 0.51 IN**

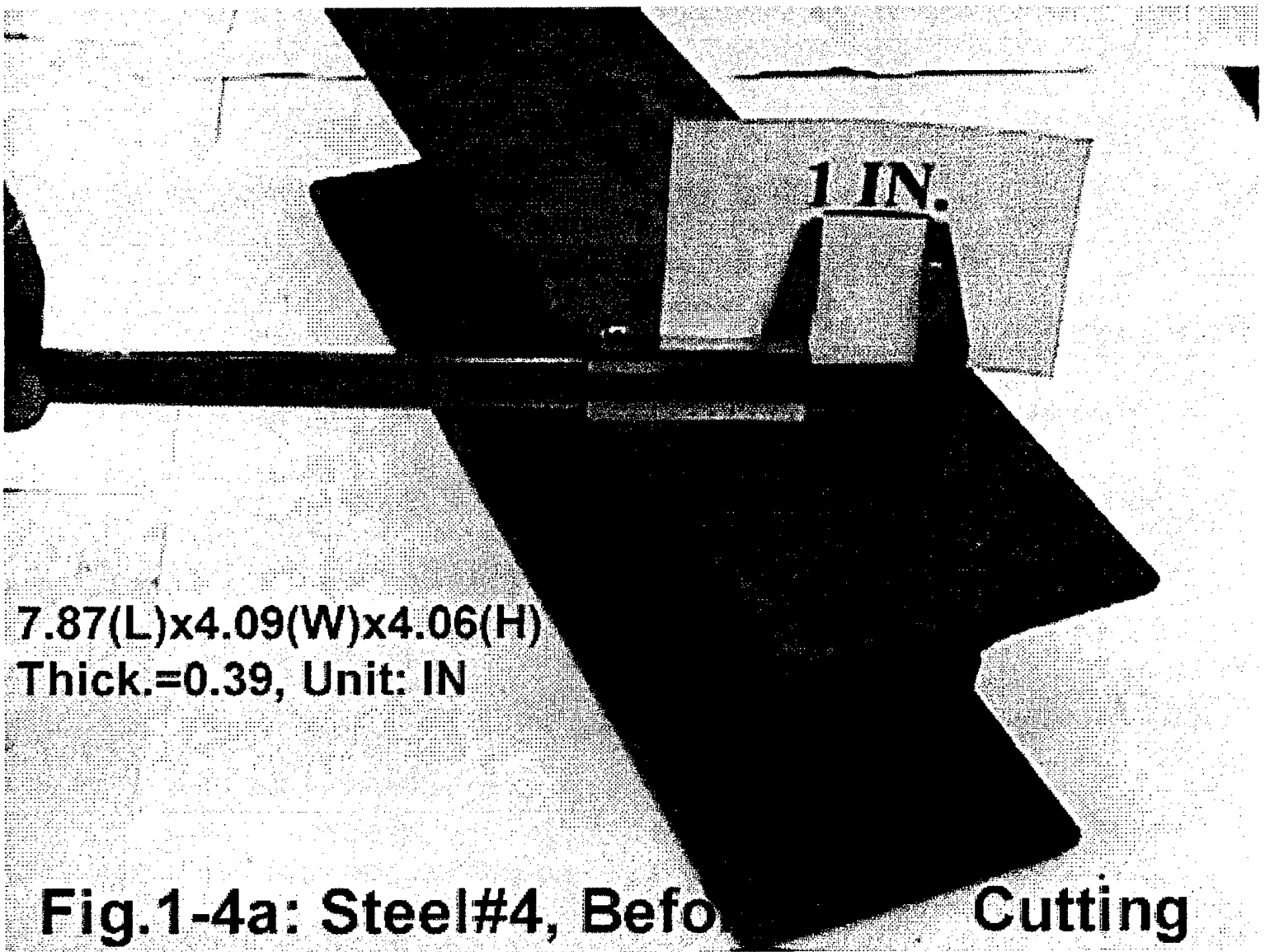


**Fig.1-3a: Steel#3, Before Cutting**

**Cutting Length = 11.81 IN,  
Time: 45 s (Tip #4); 110 s (Tip #1)**



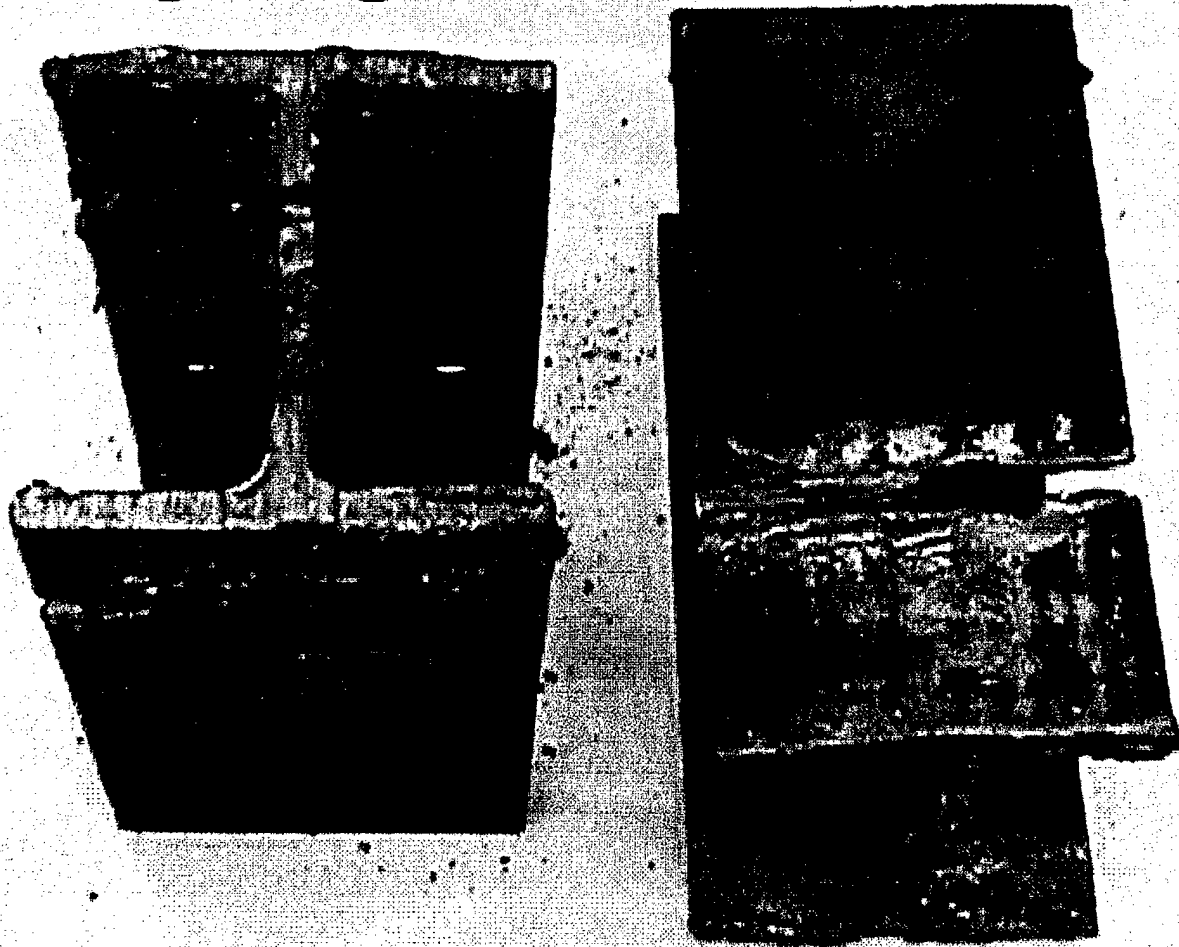
**Fig.1-3b: Steel #3, After Cutting**



7.87(L)x4.09(W)x4.06(H)  
Thick.=0.39, Unit: IN

Fig.1-4a: Steel#4, Before Cutting

**Cutting Length = 12.24 IN, Time= 41 s**



**Fig.1-4b: Steel #4, After Cutting**



**12.20 IN x 1.97 IN x 1.06 IN**

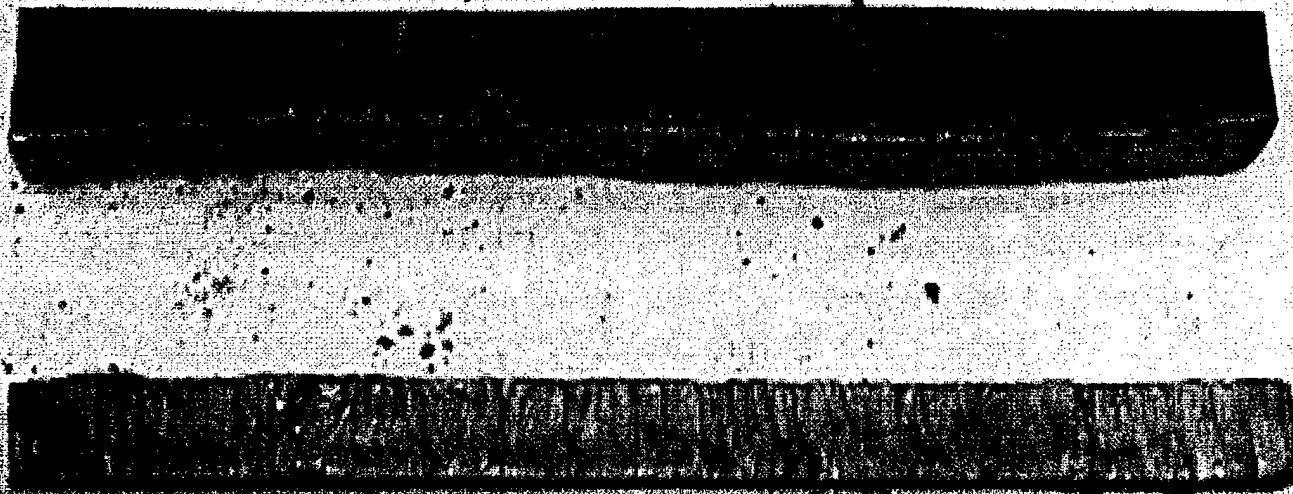
**1 IN.**



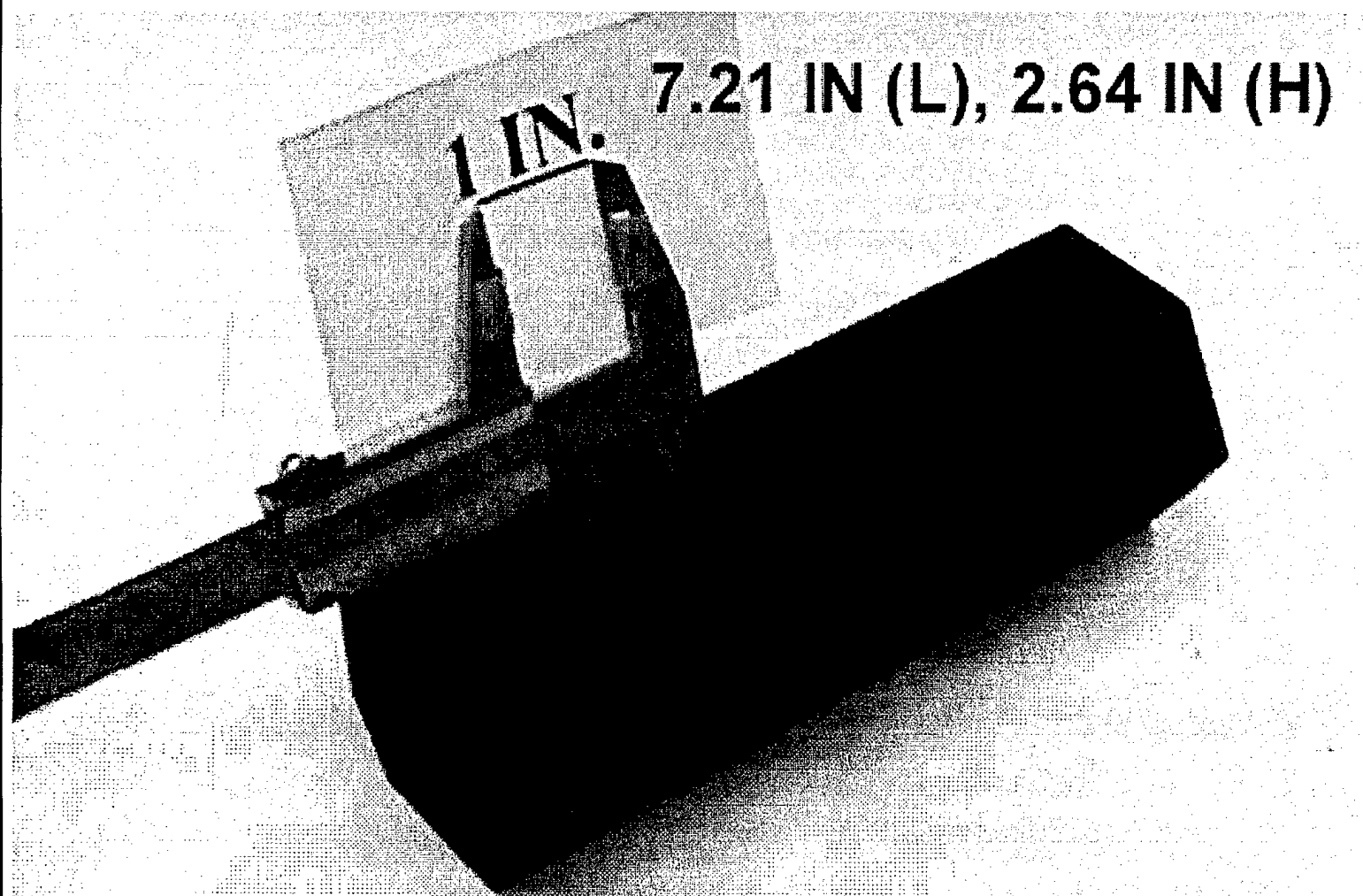
**Fig.1-5a: Steel#5, Before Cutting**



**Cutting Length = 12.20 IN, Time = 48 s**

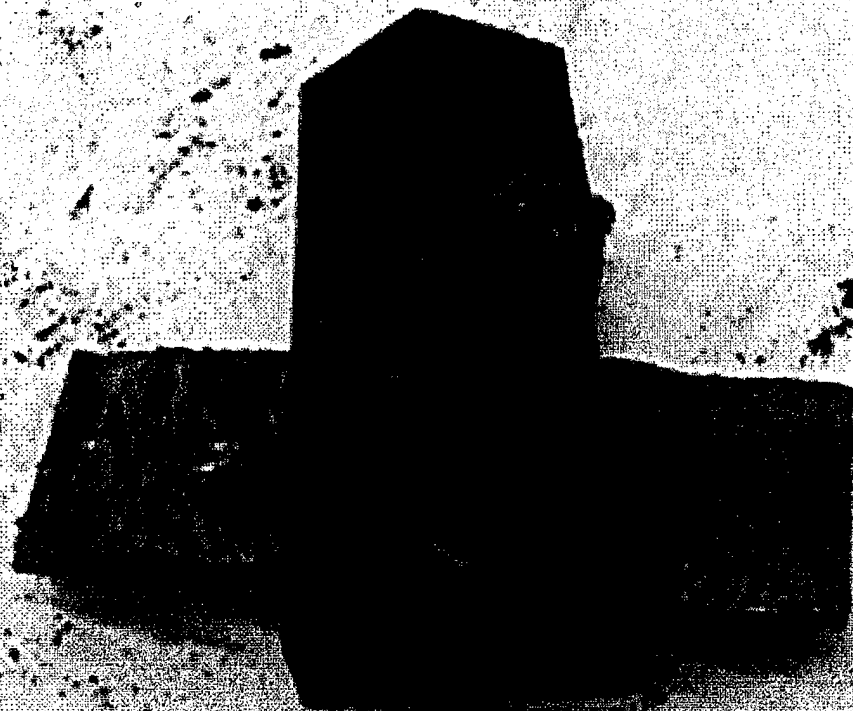


**Fig.1-5b: Steel #5, After Cutting**

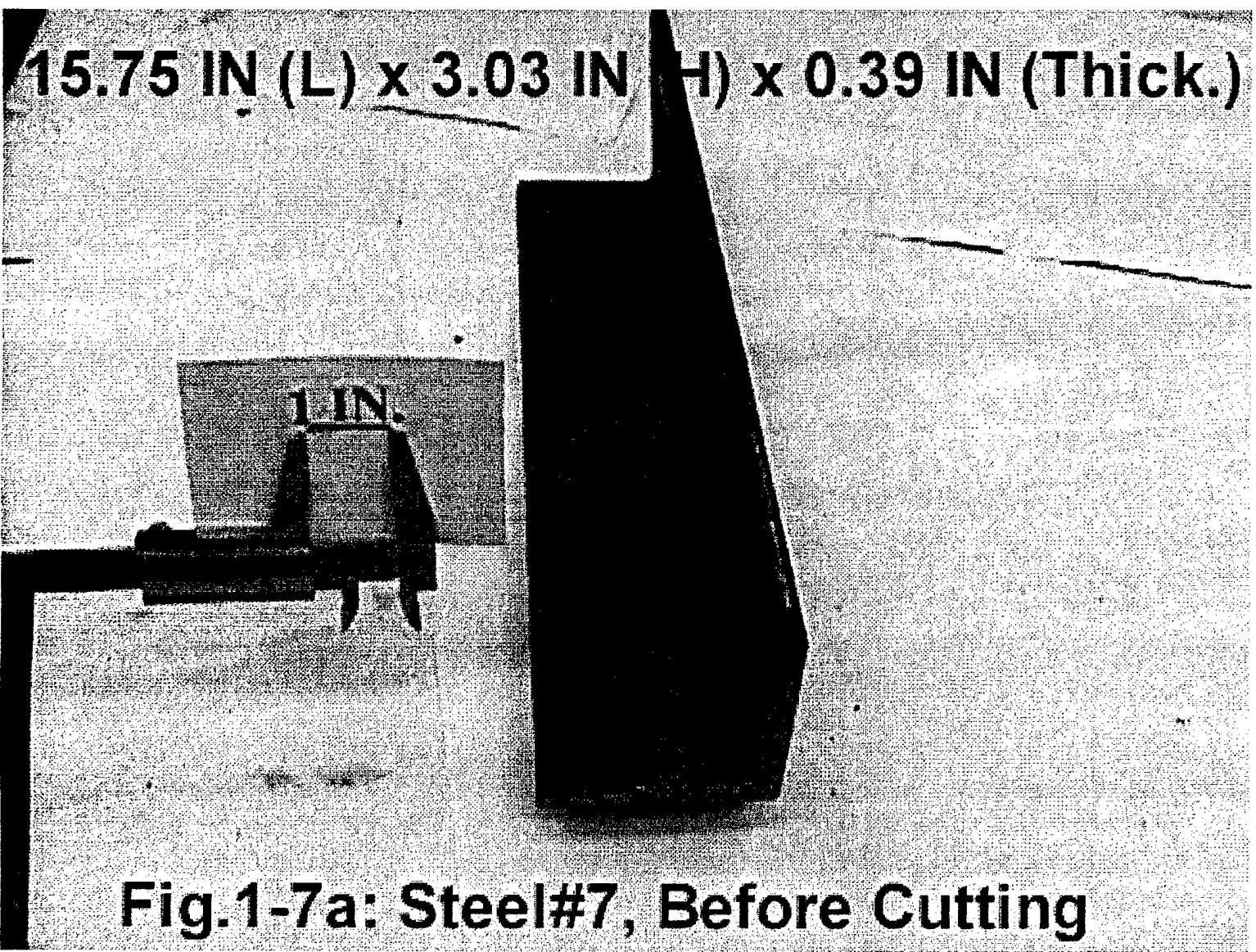


**Fig.1-6a: Steel#6, Before Cutting**

**Cutting Area = 19.01 SQ.IN., Time= 42 s**



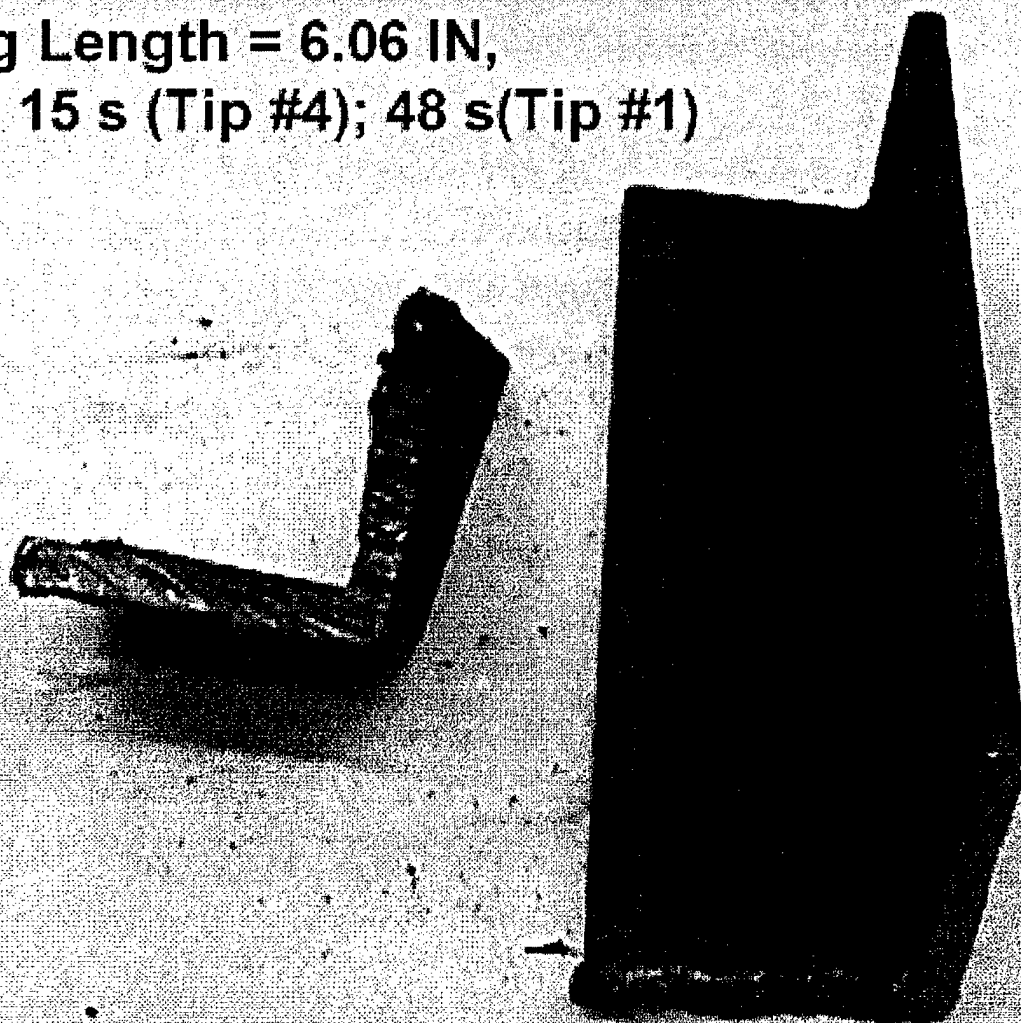
**Fig.1-6b: Steel #6, After Cutting**



**15.75 IN (L) x 3.03 IN (H) x 0.39 IN (Thick.)**

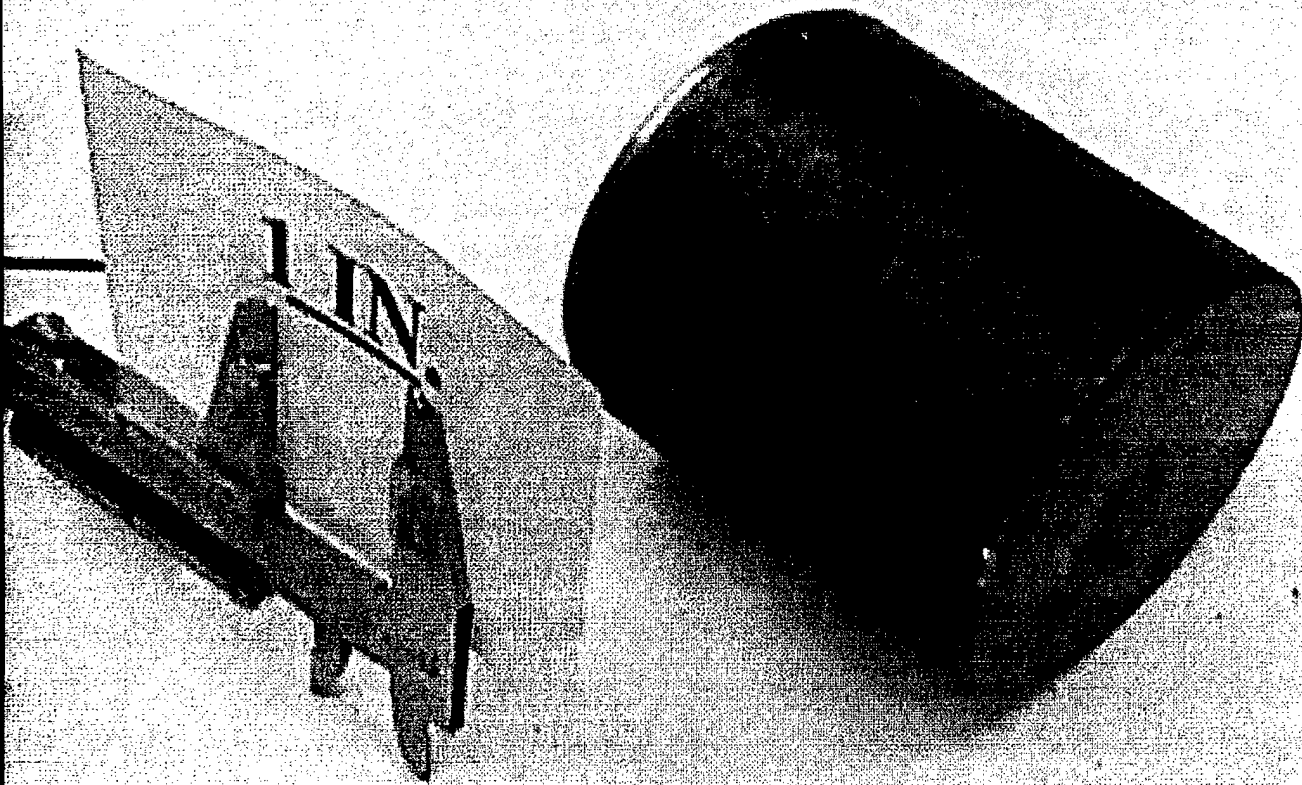
**Fig.1-7a: Steel#7, Before Cutting**

**Cutting Length = 6.06 IN,  
Time= 15 s (Tip #4); 48 s(Tip #1)**




**Fig.1-7b: Steel #7, After Cutting**

**D=2.95 IN, L=3.27 IN**



**Fig.1-8a: Steel#8, Before Cutting**





Cutting Area  
3.54 SQ.IN.  
Time=43 s

**Fig.1-8b: Steel #8, After Cutting**

**9.06 IN (L) x 1.73 IN (H)**

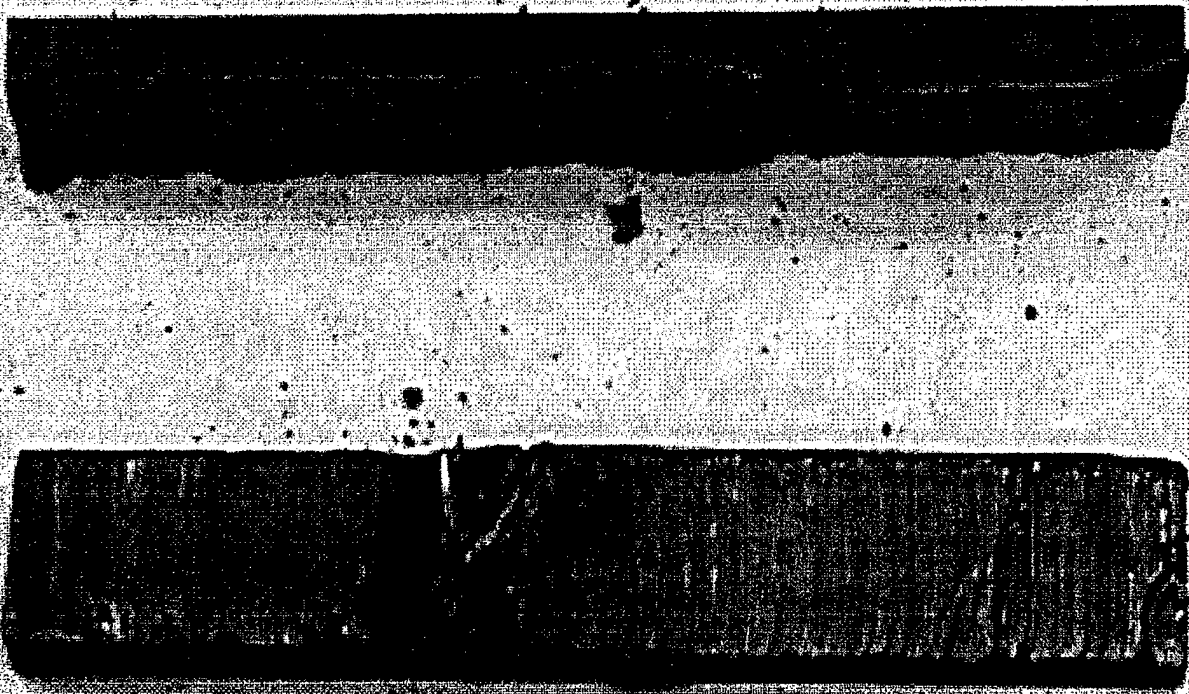
**1 IN.**



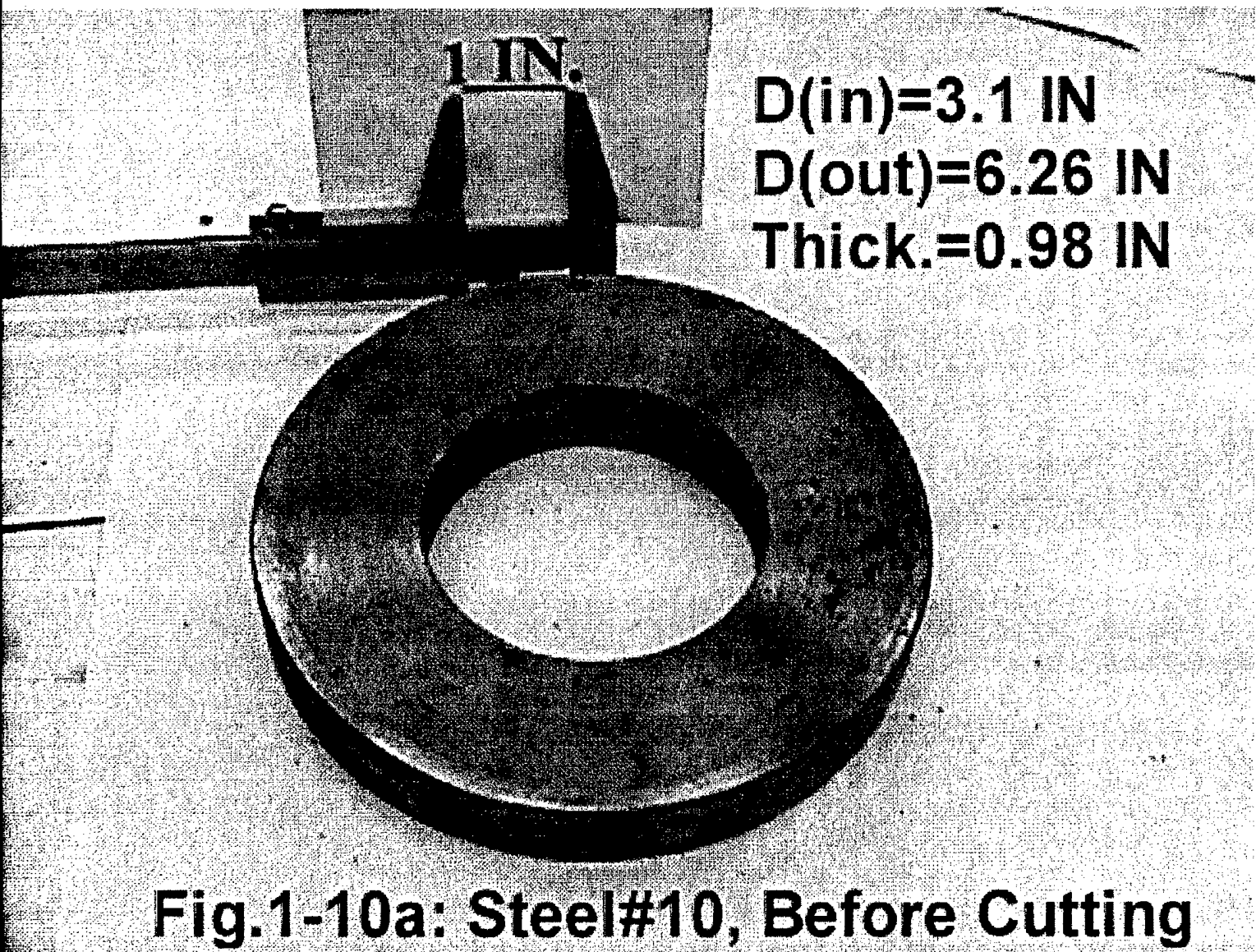
**Fig.1-9a: Steel#9, Before Cutting**



**Cutting Area = 16.61 SQ.IN., Time= 57 s**



**Fig.1-9b: Steel #9, After Cutting**

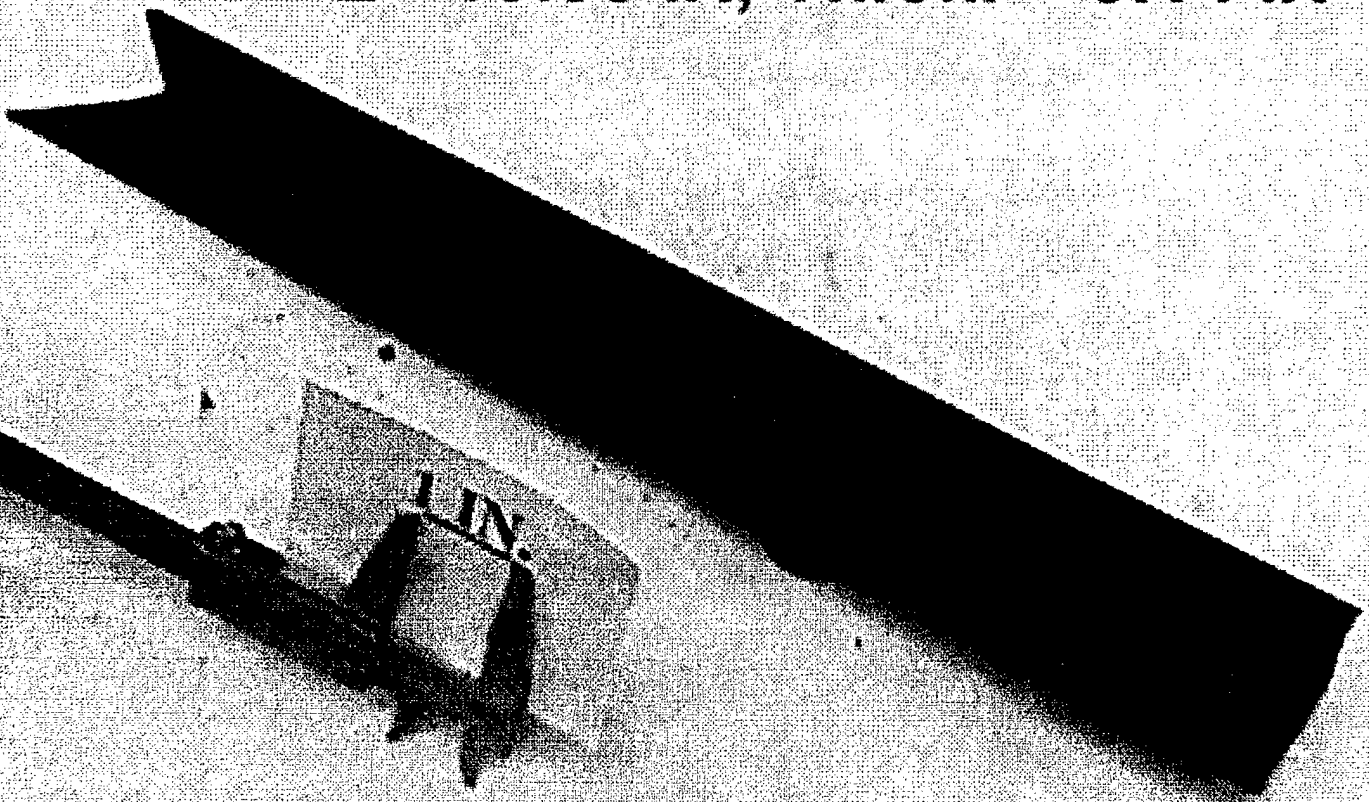


**Cutting Area = 1.55 SQ.IN., Time= 16 s**



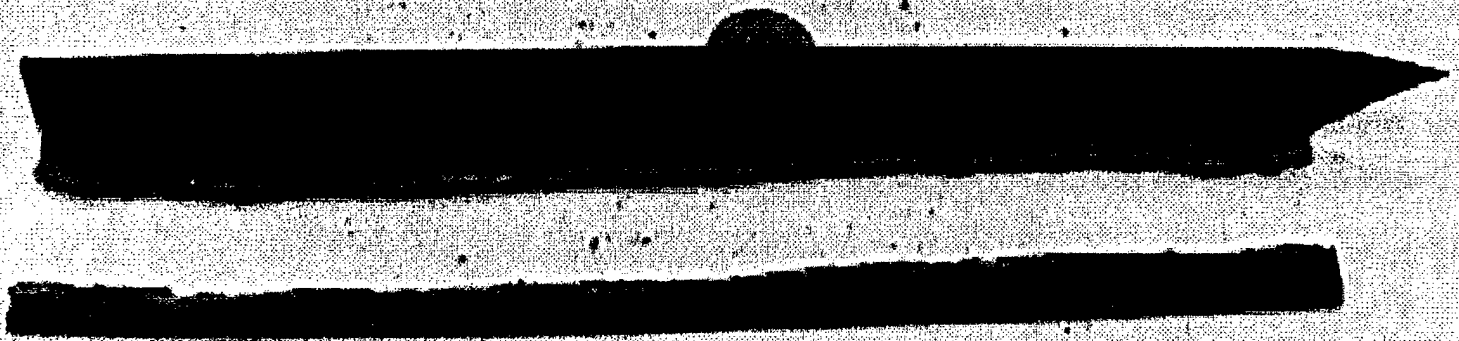
**Fig. 1-10b: Steel #10, After Cutting**

**$L = 15.35 \text{ IN}$ ; Thick. =  $0.14 \text{ IN}$**



**Fig.1-11a: Steel #11, Before Cutting**

**Cutting Length = 15.25 IN, Time = 41 s (Tip #)**



**Fig.1-11b: Steel #11, After Cutting**

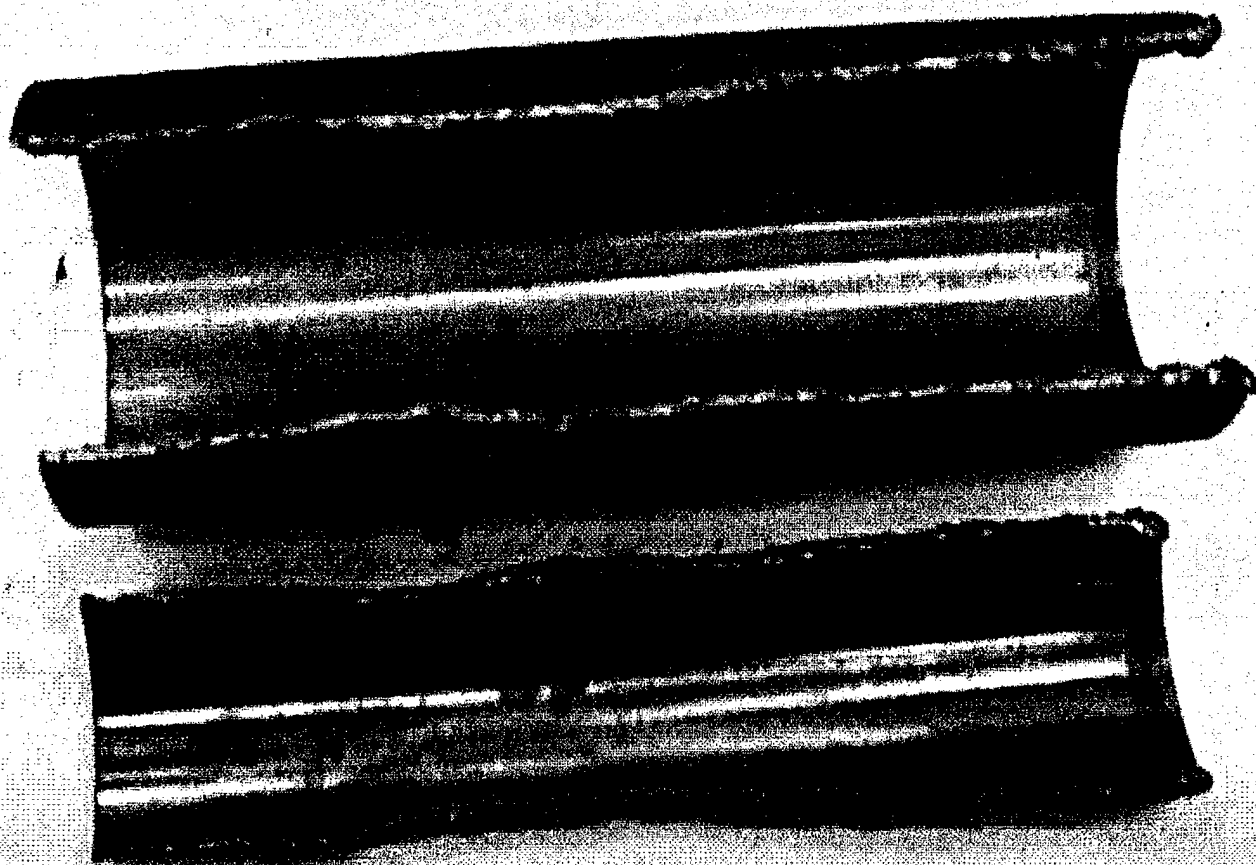
**$L = 10.63 \text{ IN}$ , Thick. =  $0.14 \text{ IN}$**



**Fig.1-12a: Steel #12, Before Cutting**

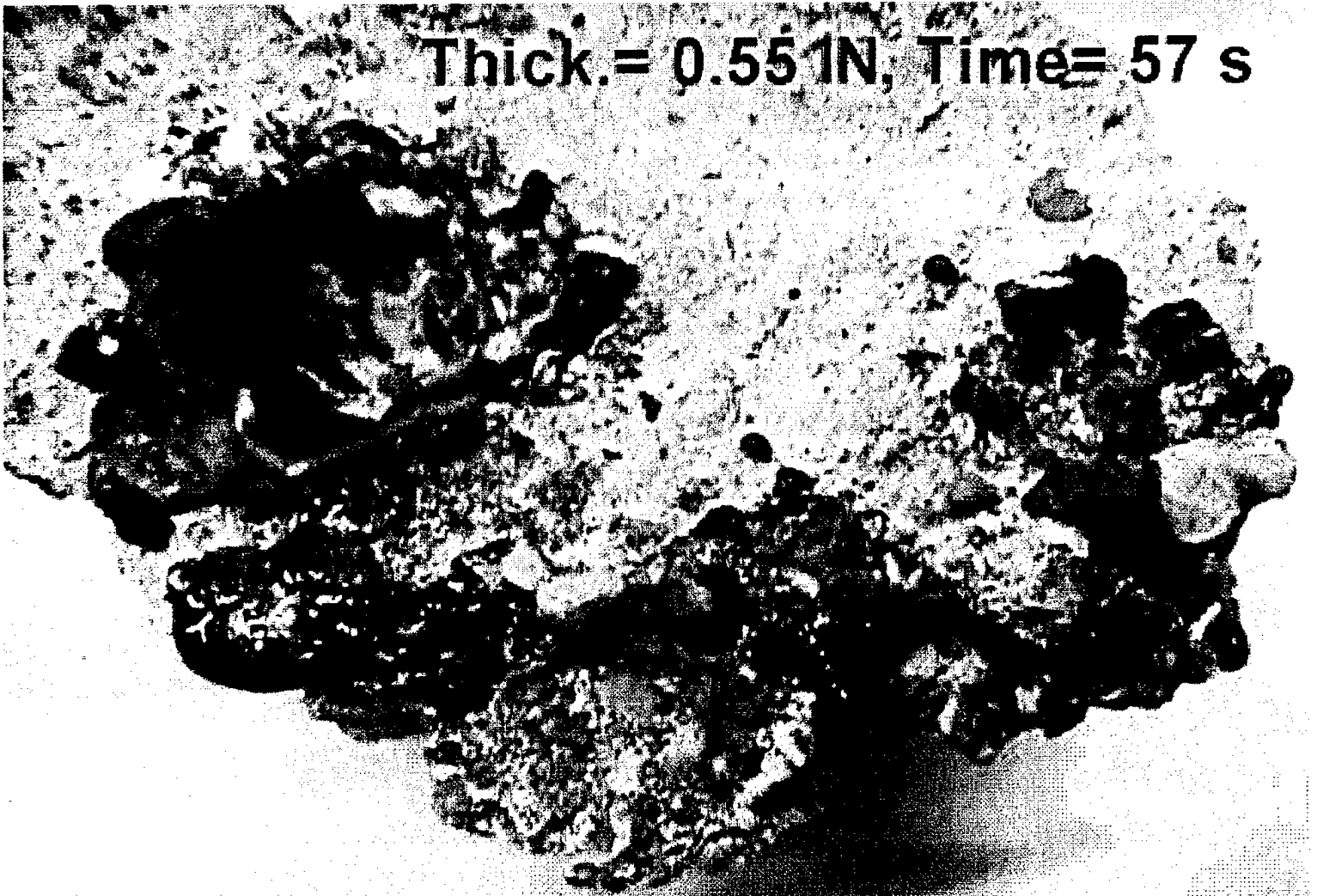


**Cutting Length = 10.63 IN, Time= 44 s (Tip#1)**



**Fig.1-12b: Steel #12, After Cutting**

**Thick. = 0.55 1N, Time = 57 s**



**Fig.1-13: Concrete#1, After Cutting**



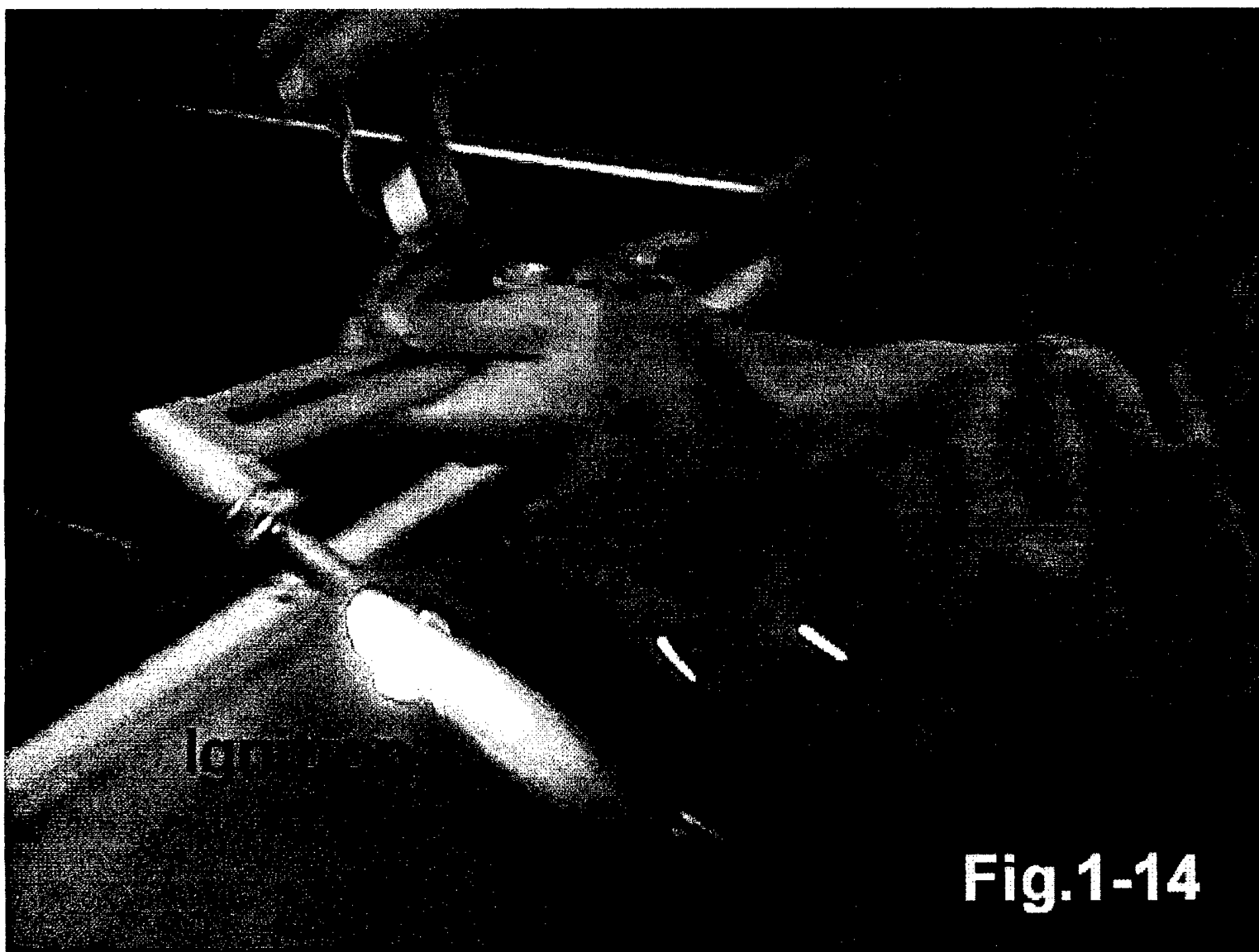
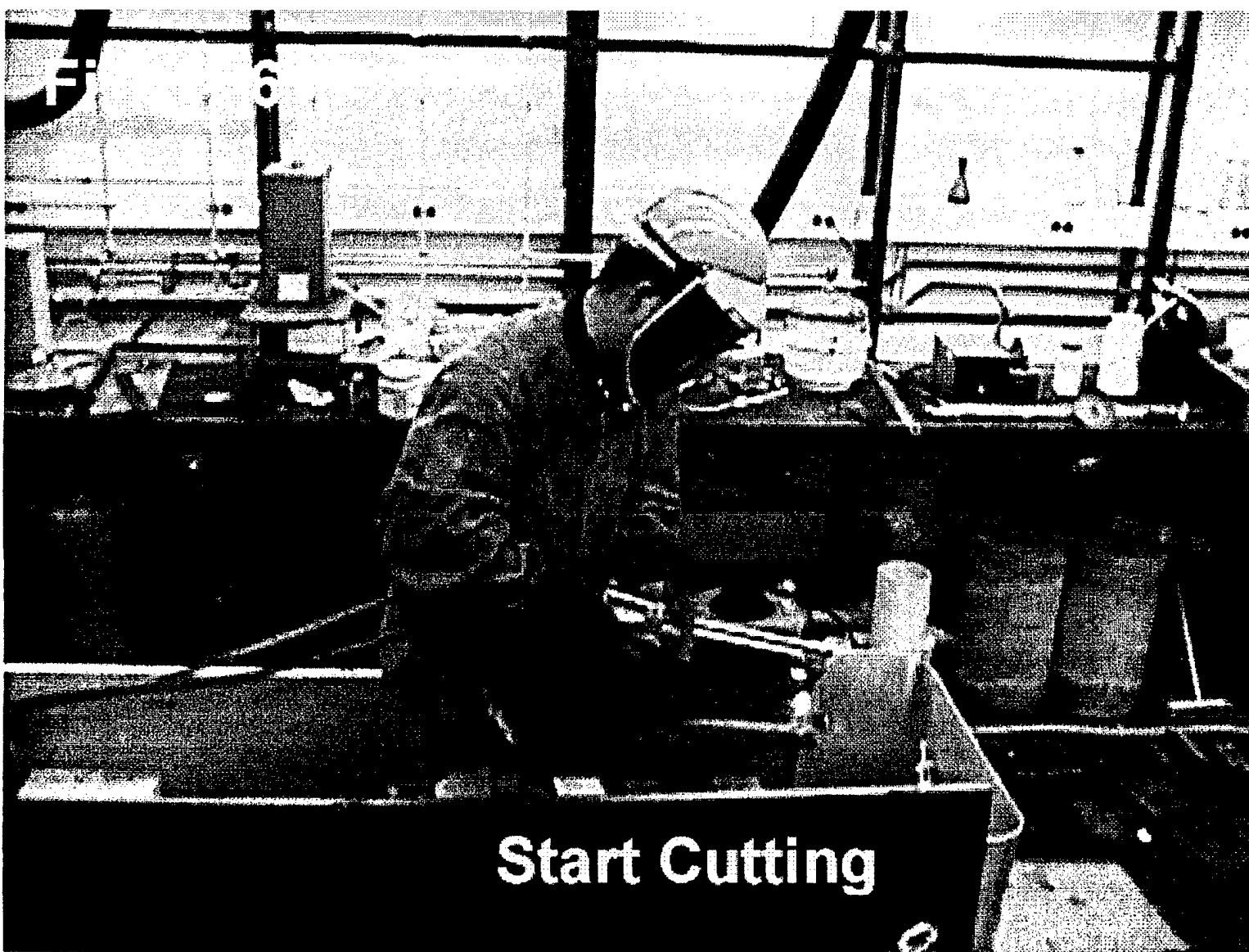


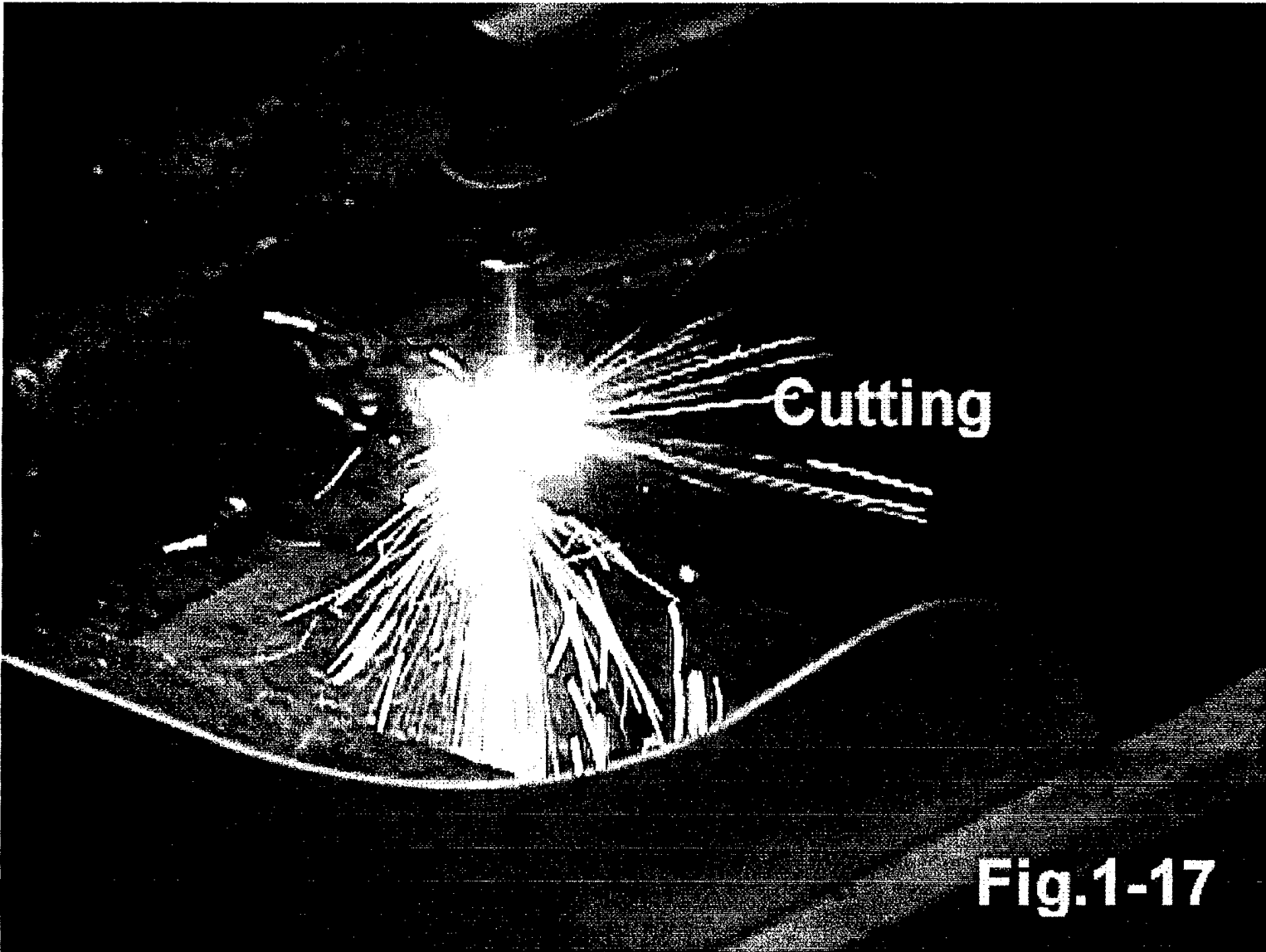


Fig. 1-35

## Flame Adjustment

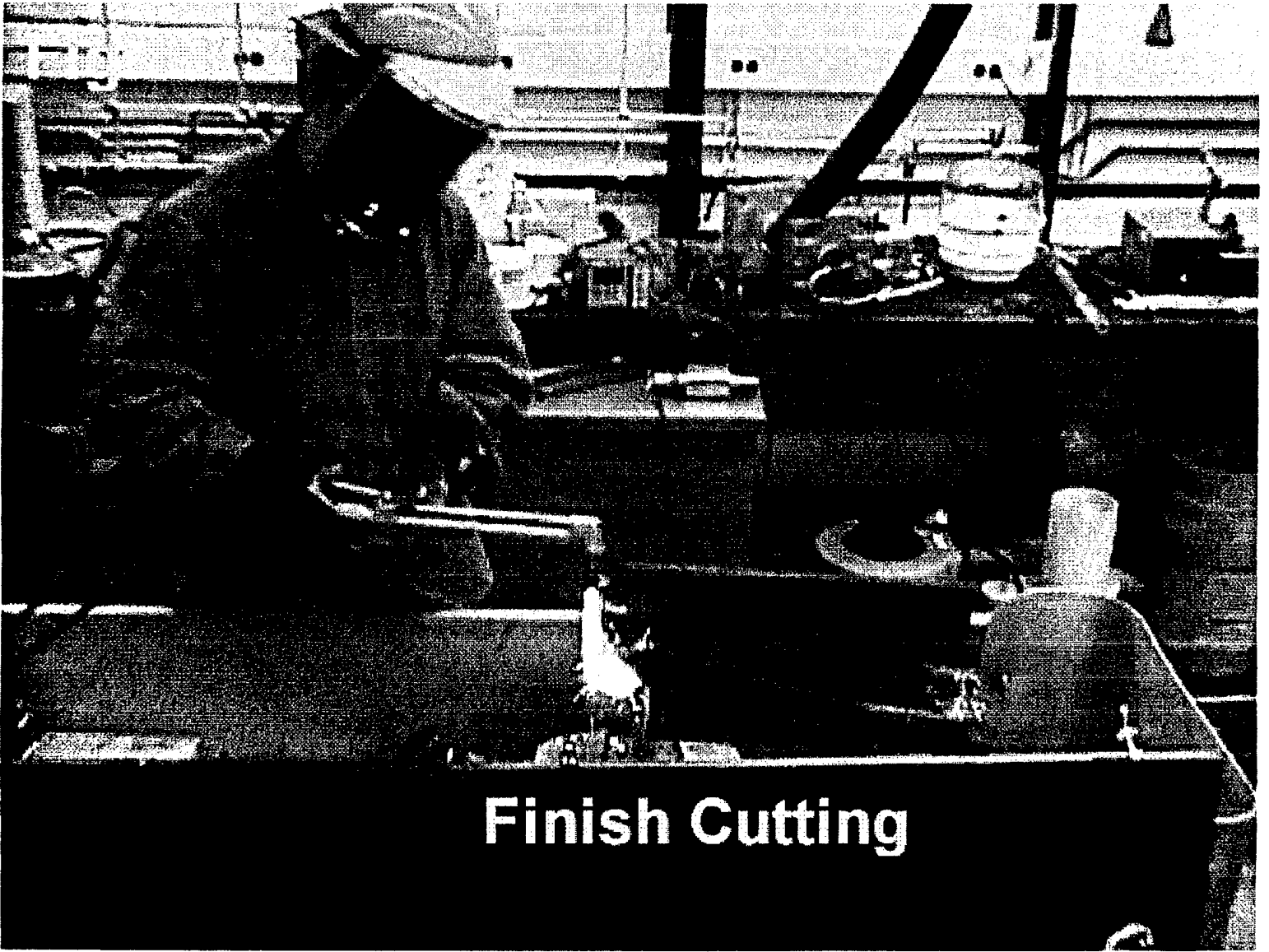


**Start Cutting**





Cutting



**Finish Cutting**

### **III.3.The Oxy lance Cutting Torch**

The Oxy lance cutting torch system manufactured by Broco Company was installed and tested. Metal burning bars of 1/4", 3/8" and 1/2" were used. The manufacturer claims that the burning action of the metal bars and oxygen liquefies many metallic materials in their path and cuts almost any known material.

#### **III.3.1. Cutting of iron material**

Steel rods of different diameters and steel plates of different thickness were cut by using the Oxy lance Cutting Torch. Photographs of the workpieces after cutting are shown in Figures 2.1 to 2.15. Data on cutting of the workpieces are recorded in particular figures. Both cutting and piercing of the steel pieces were carried out.

The torch package consists of a burning rod handle, a 12-volt battery and a striker plate for ignition, and a high volume regulator and hose. The 3/8" x 36" burning rods and industrial grade oxygen (99.5% O<sub>2</sub>) were used for the cutting experiments. Oxygen pressure was set to 50 psi. The oxygen consumption is a function of the size of the burning rod and the pressure of oxygen set. The average oxygen consumption for 3/8"x36" burning rod and oxygen pressure of 50 psi is 9 cf<sup>3</sup>/each rod.

The oxy lance cutting torch system and operation procedures are presented in Figures 2.16-2.19.

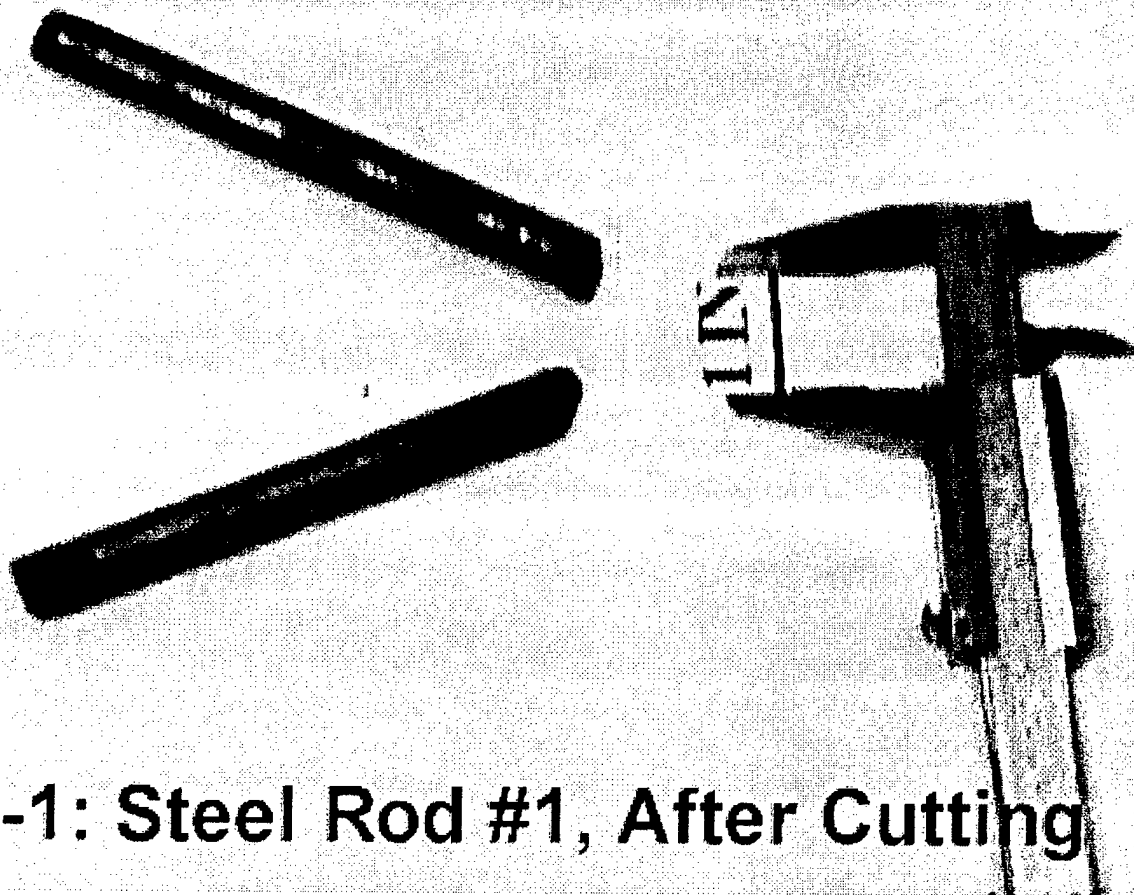
#### **III.3.2. Cutting of concrete**

A concrete plate of thickness =1.6 inches was collected from a construction site. A hole of diameter=1.5 inches was pierced in 52 seconds. Figs 2.15a and 2.15b show the pierced concrete piece. Our experiments reveal that concrete can be penetrated by the lance.

### **III.4. Preparation and cutting of reinforced concrete sample plates**

Reinforced concrete plates of different thickness have been fabricated in house. With the plates we prepared, the cutting data on the samples of known composition can be collected. Below we will discuss the results of these experiments in detail

**D= 0.42 IN, Time= 2 S**



**Fig.2-1: Steel Rod #1, After Cutting**

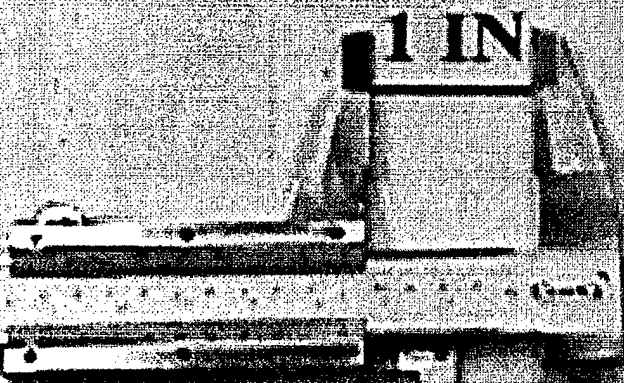


**D= 0.74 IN, Time= 3 S**



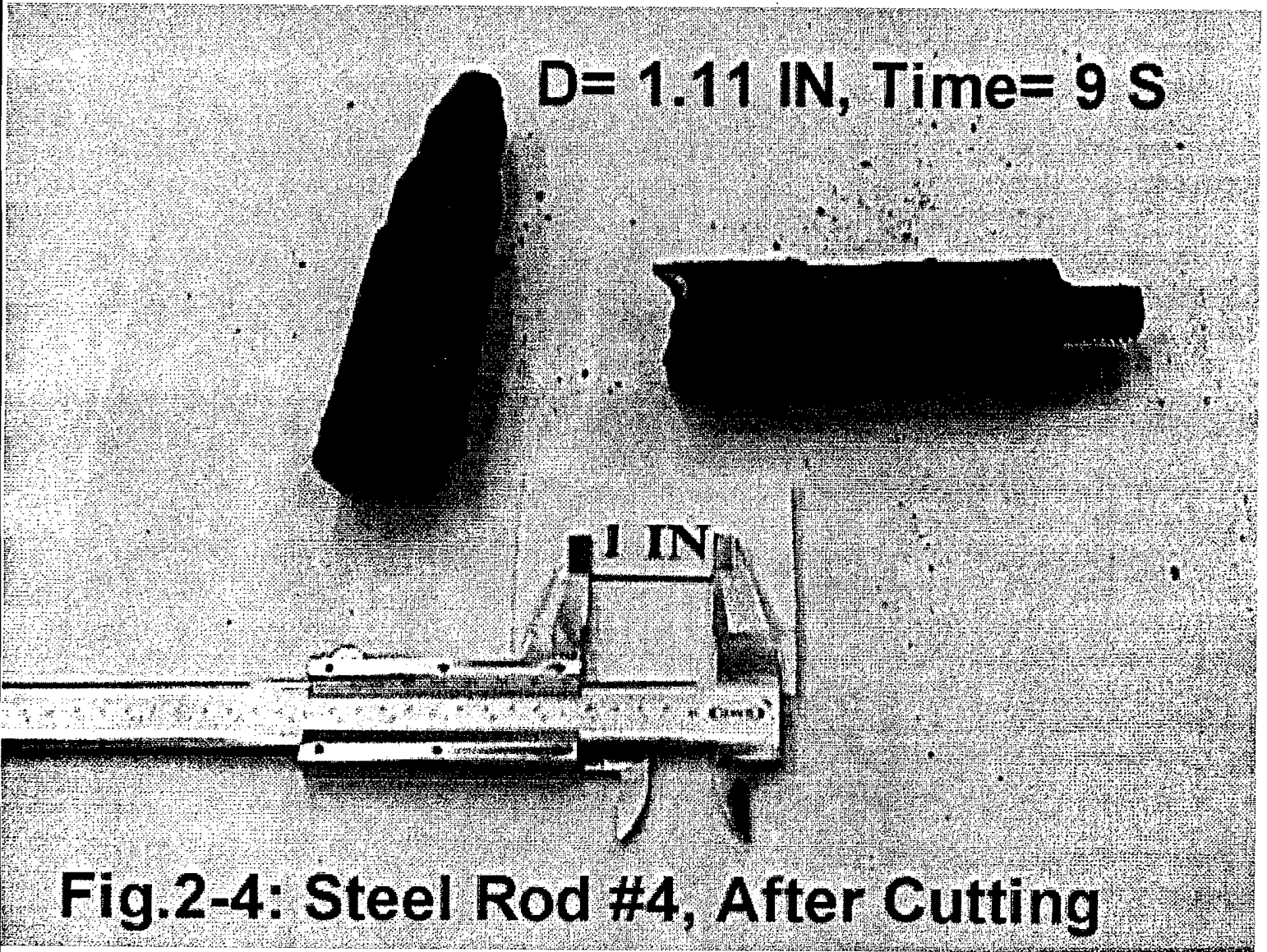
**Fig.2-2: Steel Rod #2, After Cutting**

**D= 0.84 IN, Time= 11 S**



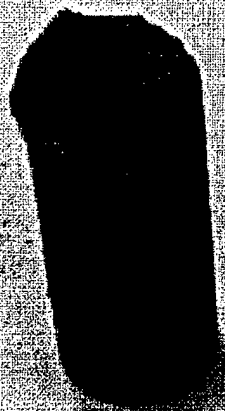
**Fig.2-3: Steel Rod #3, After Cutting**

**D= 1.11 IN, Time= 9 S**

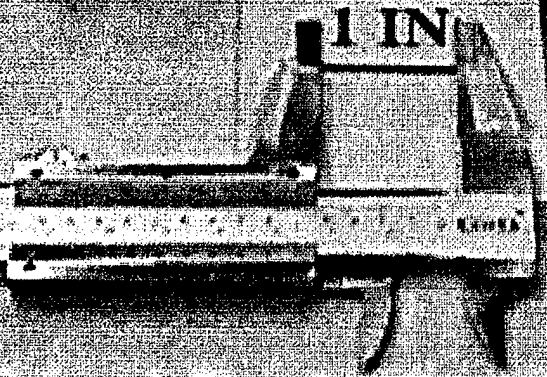


**Fig.2-4: Steel Rod #4, After Cutting**

**D= 1.24 IN, Time= 9 S**



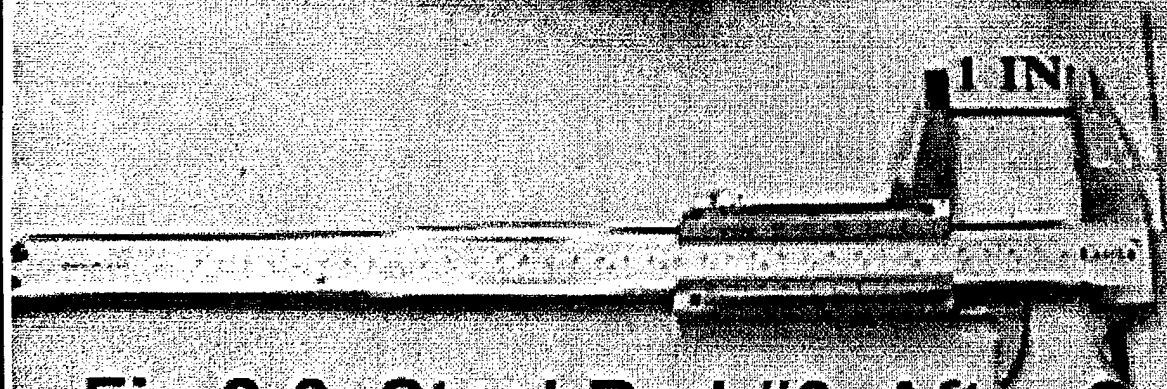
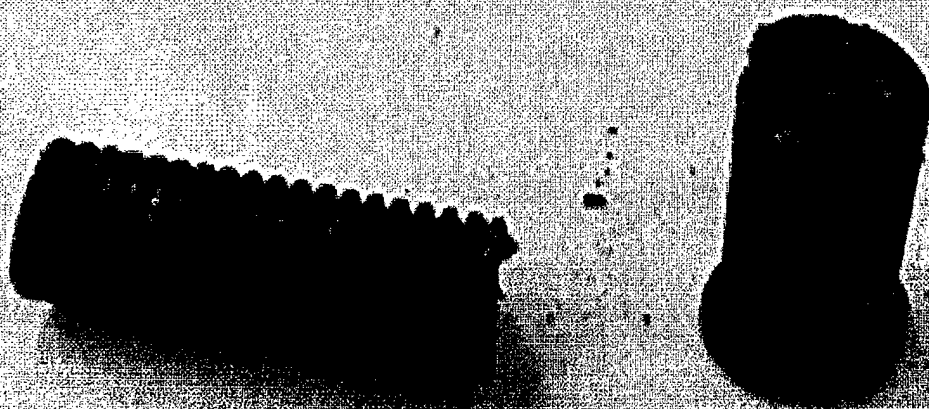
**1 IN**



**Fig.2-5: Steel Rod #5, After Cutting**



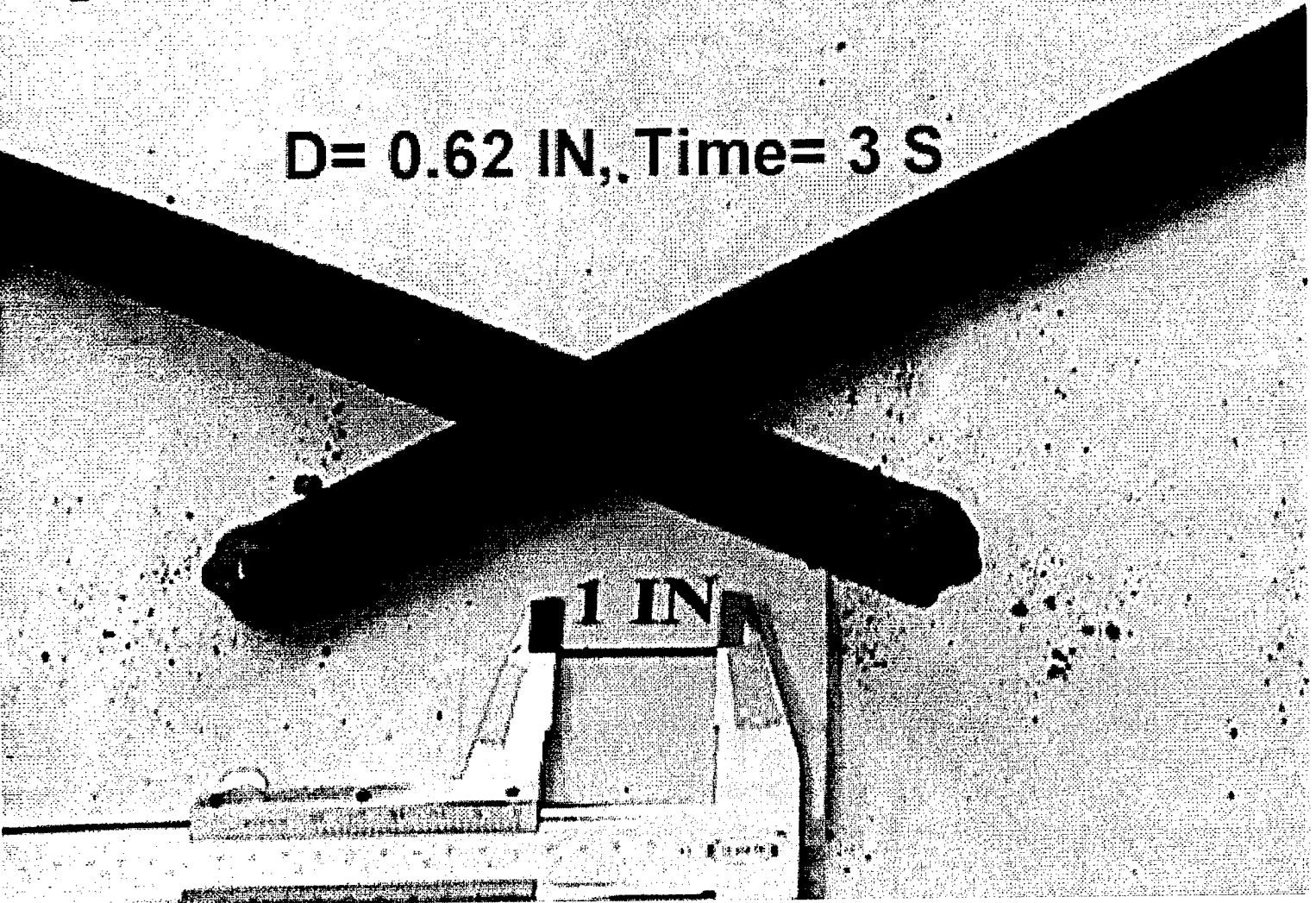
**D= 1.52 IN, Time= 9 S**



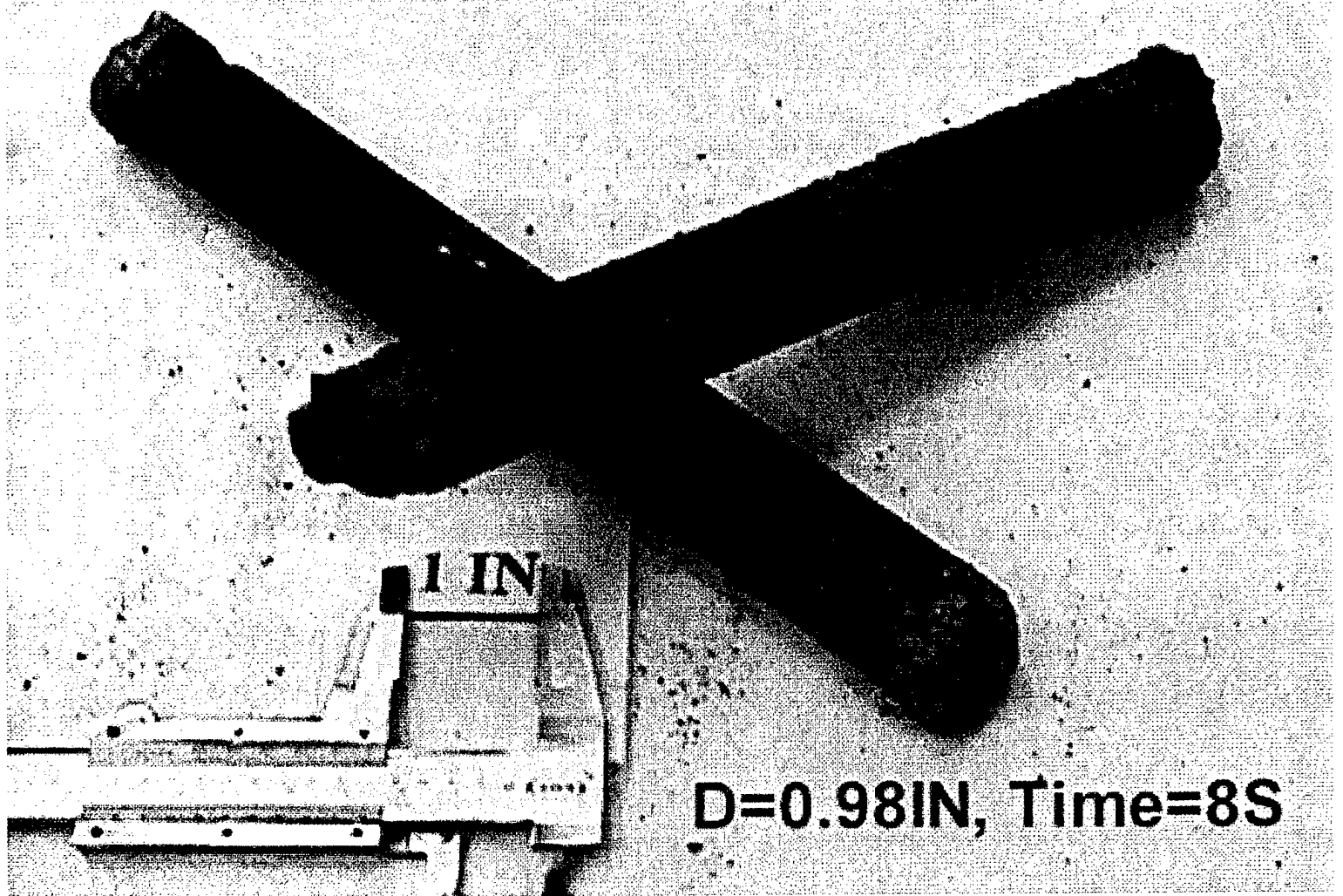
**Fig.2-6: Steel Rod #6, After Cutting**

**Fig.2-7: Reinforcing Steel#7, After Cutting**

**D= 0.62 IN, Time= 3 S**

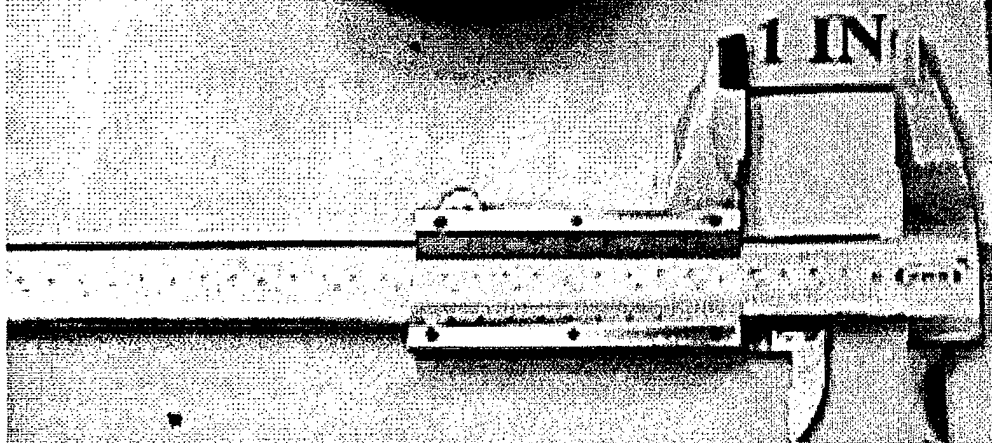


**Fig.2-8: Reinforcing Steel#8, After Cutting**

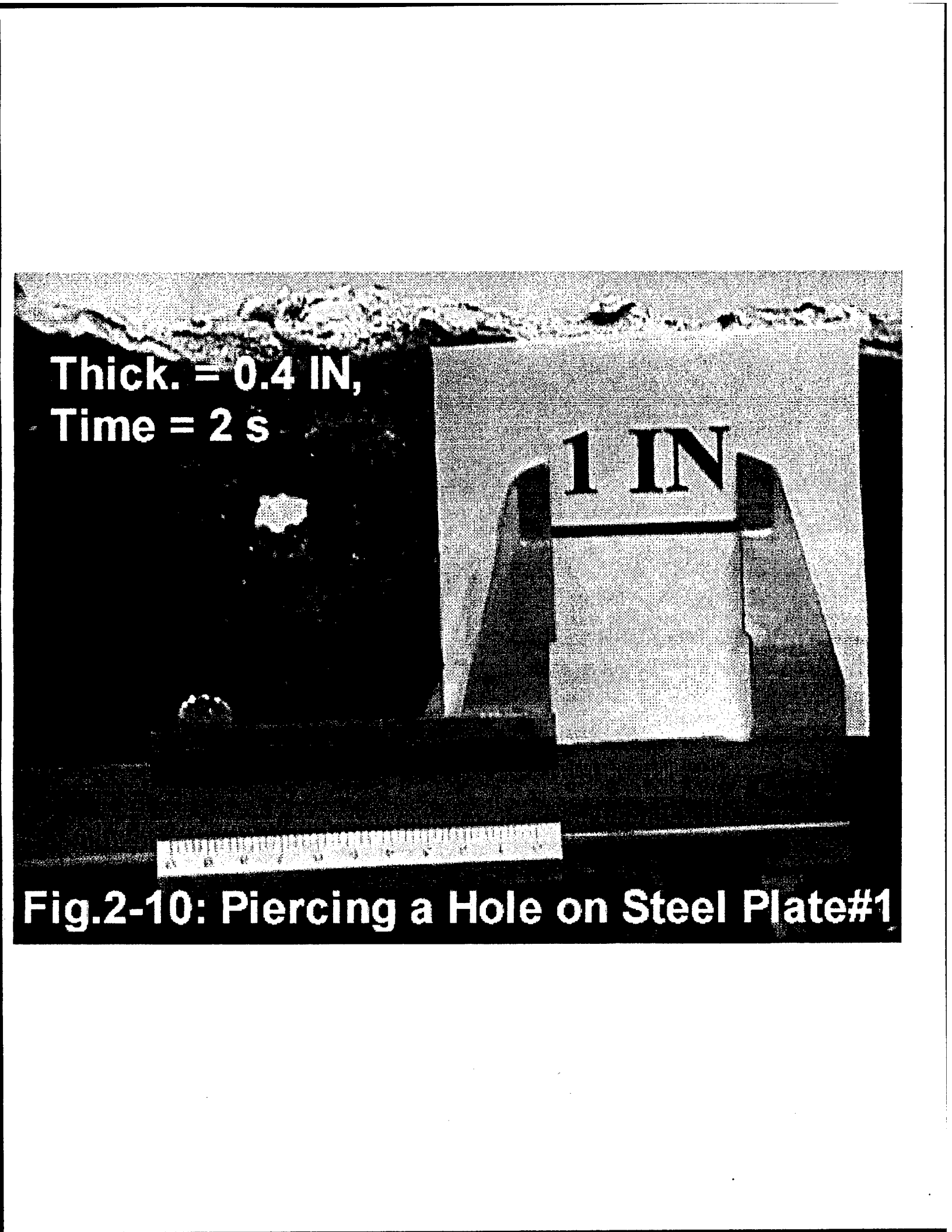


**Fig.2-9: Steel Rod#9, After Cutting**

**D=2.94 IN, Time=40 s**





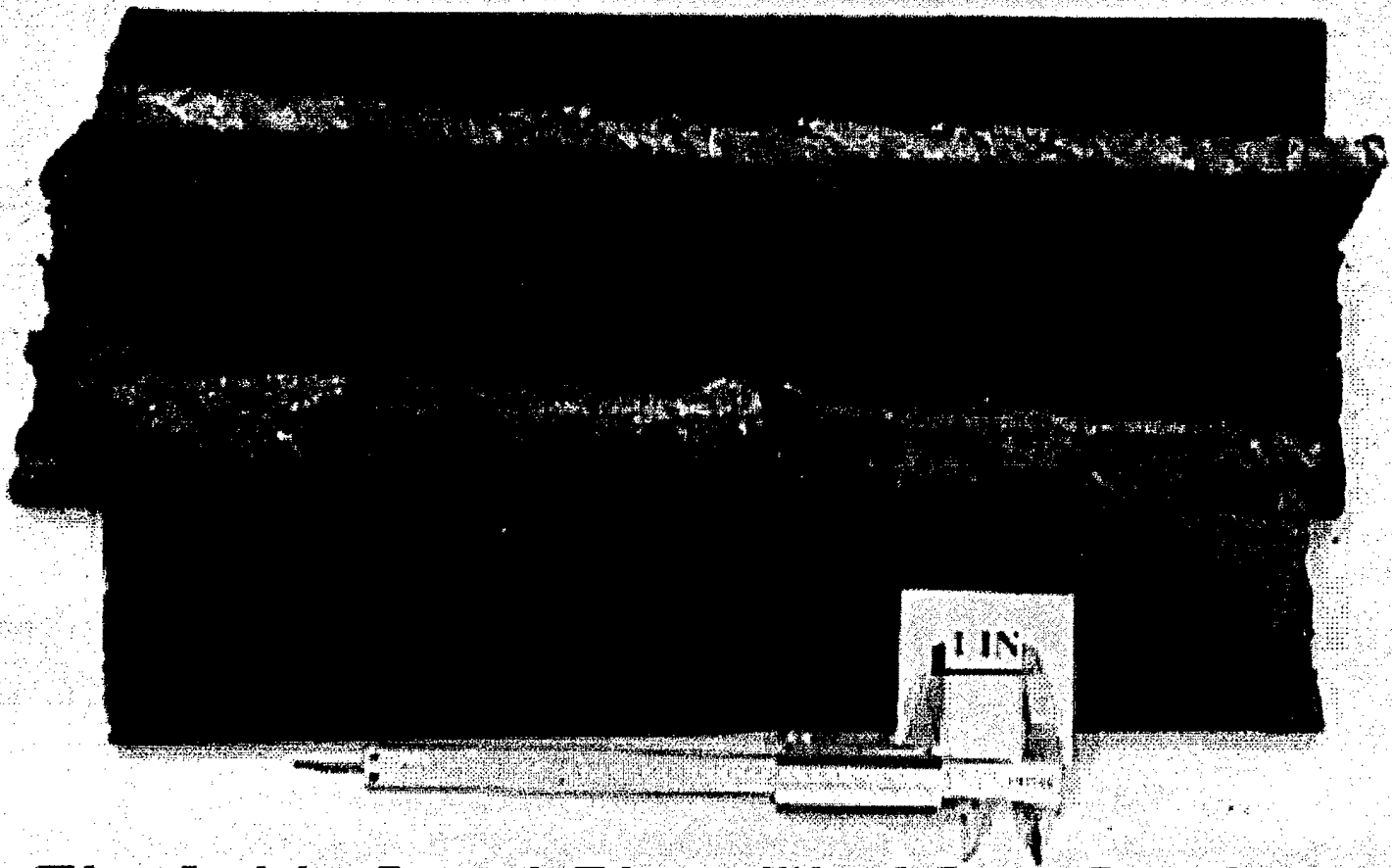


**Thick. = 0.4 IN,  
Time = 2 s**

**1 IN**

**Fig.2-10: Piercing a Hole on Steel Plate#1**

**Thick. = 0.44 IN, L=16.4 IN, Time=22S**



**Fig.2-11: Steel Plate#1, After Cutting**

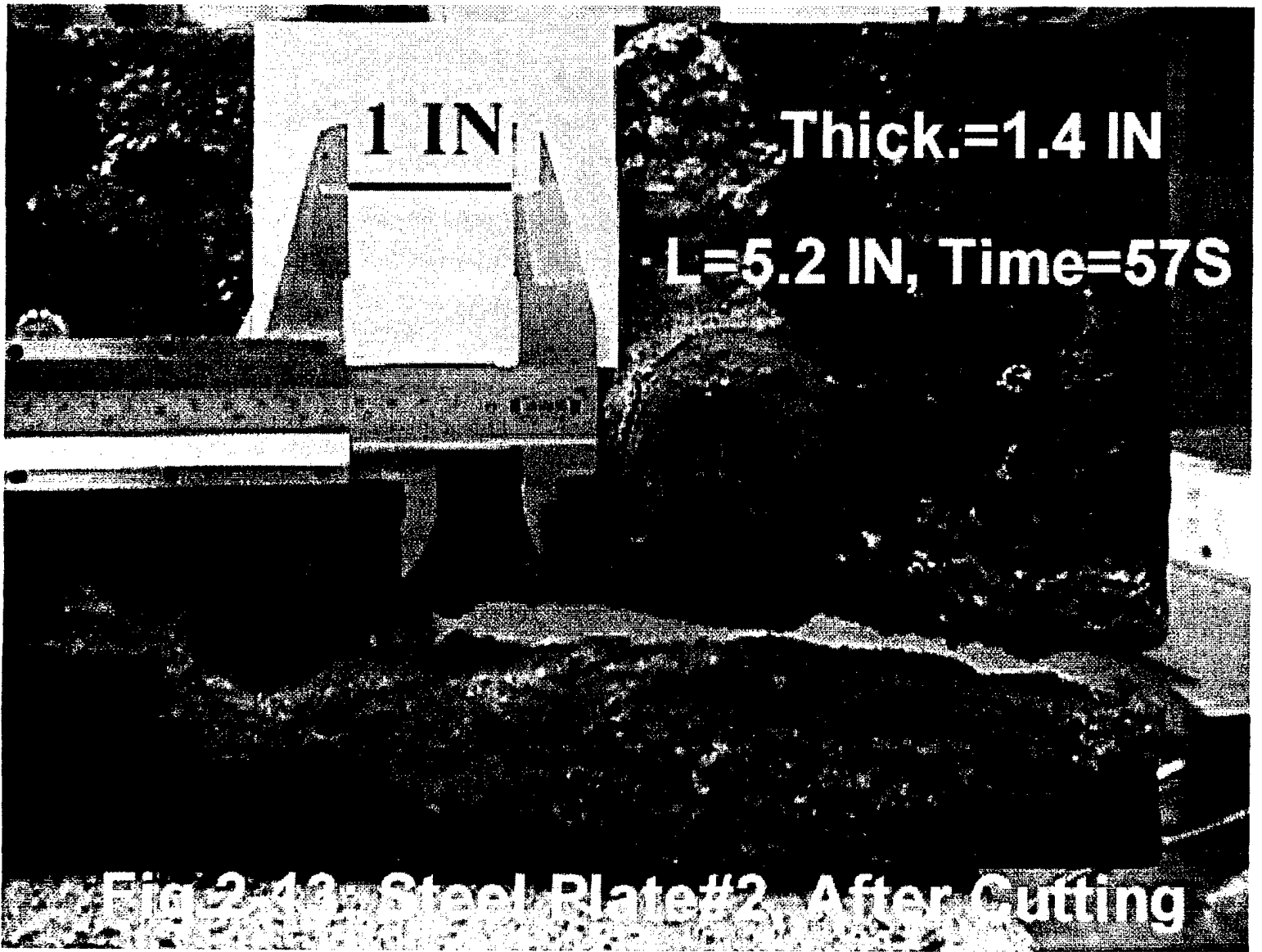


**Thick=1.4 IN**

**Time=2S**

**1 IN**

**Fig.2-12 Piercing a Hole on Steel Plate#2**





Thick.=0.5 IN, Time=1S

1 IN

Fig 2-14: Piercing a Hole on Steel Plate #3

**Piercing a Hole on Concrete Plate#1**

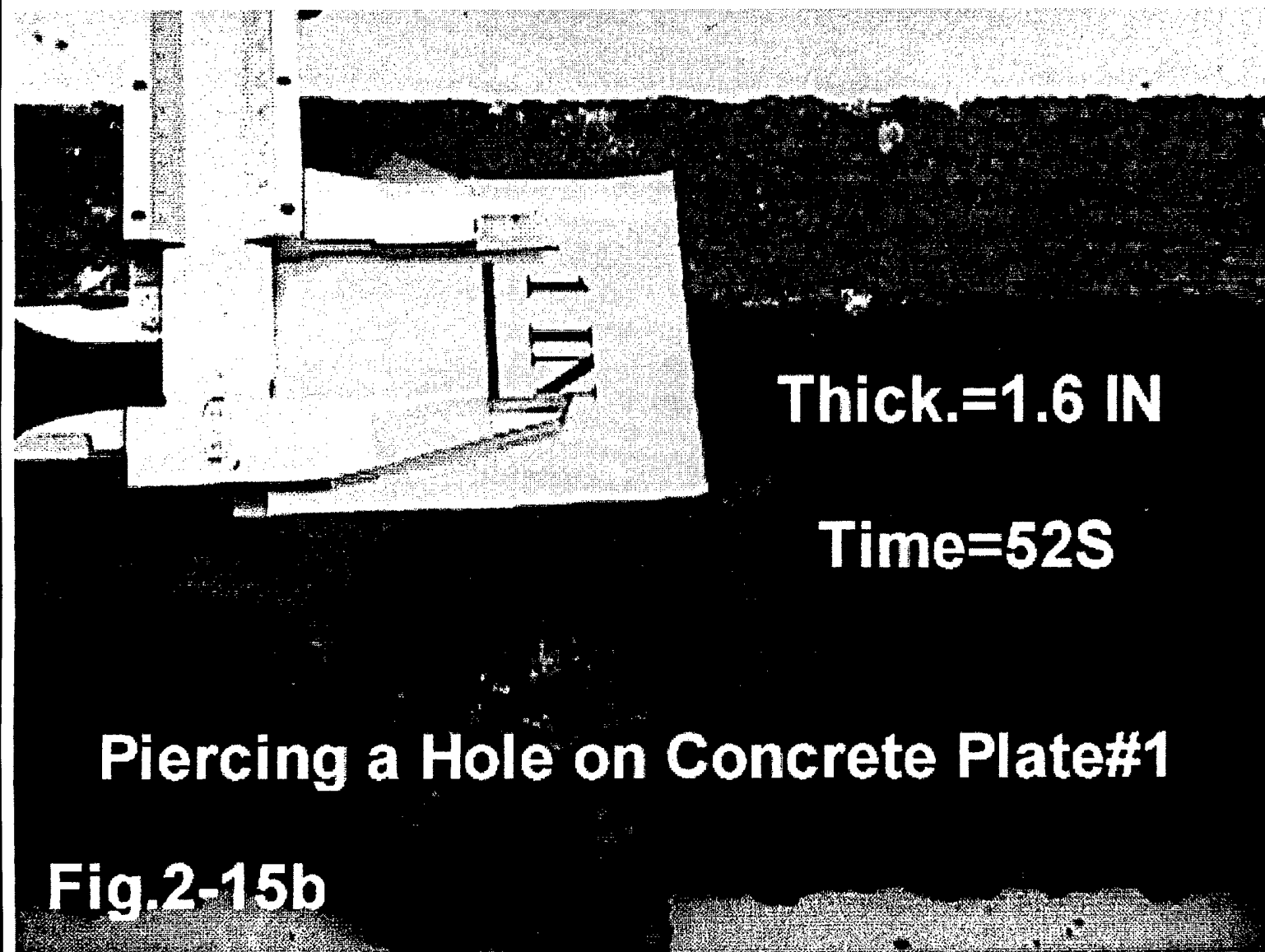
**Thick.=1.6 IN**

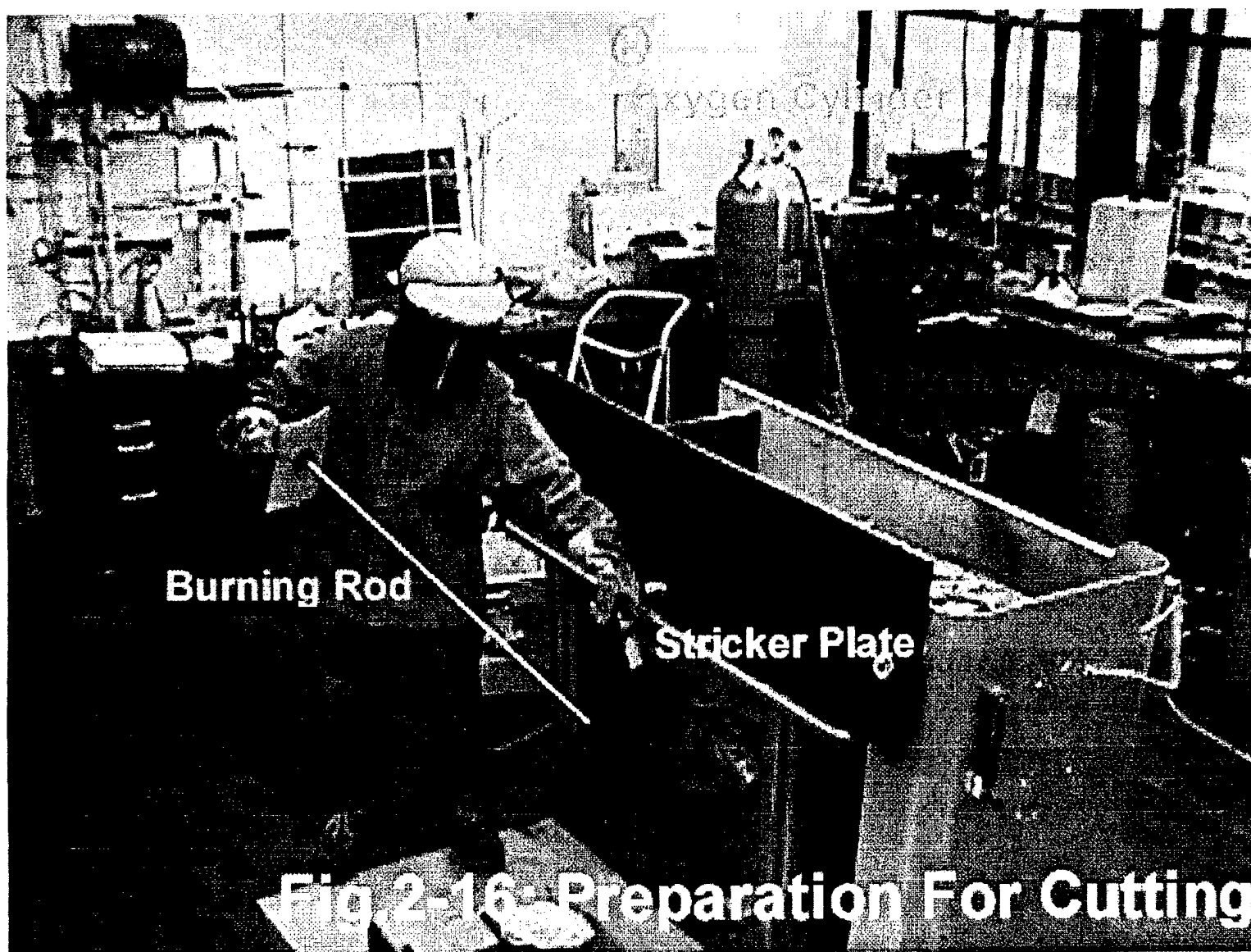
**Time=52S**

**Fig.2-15a**

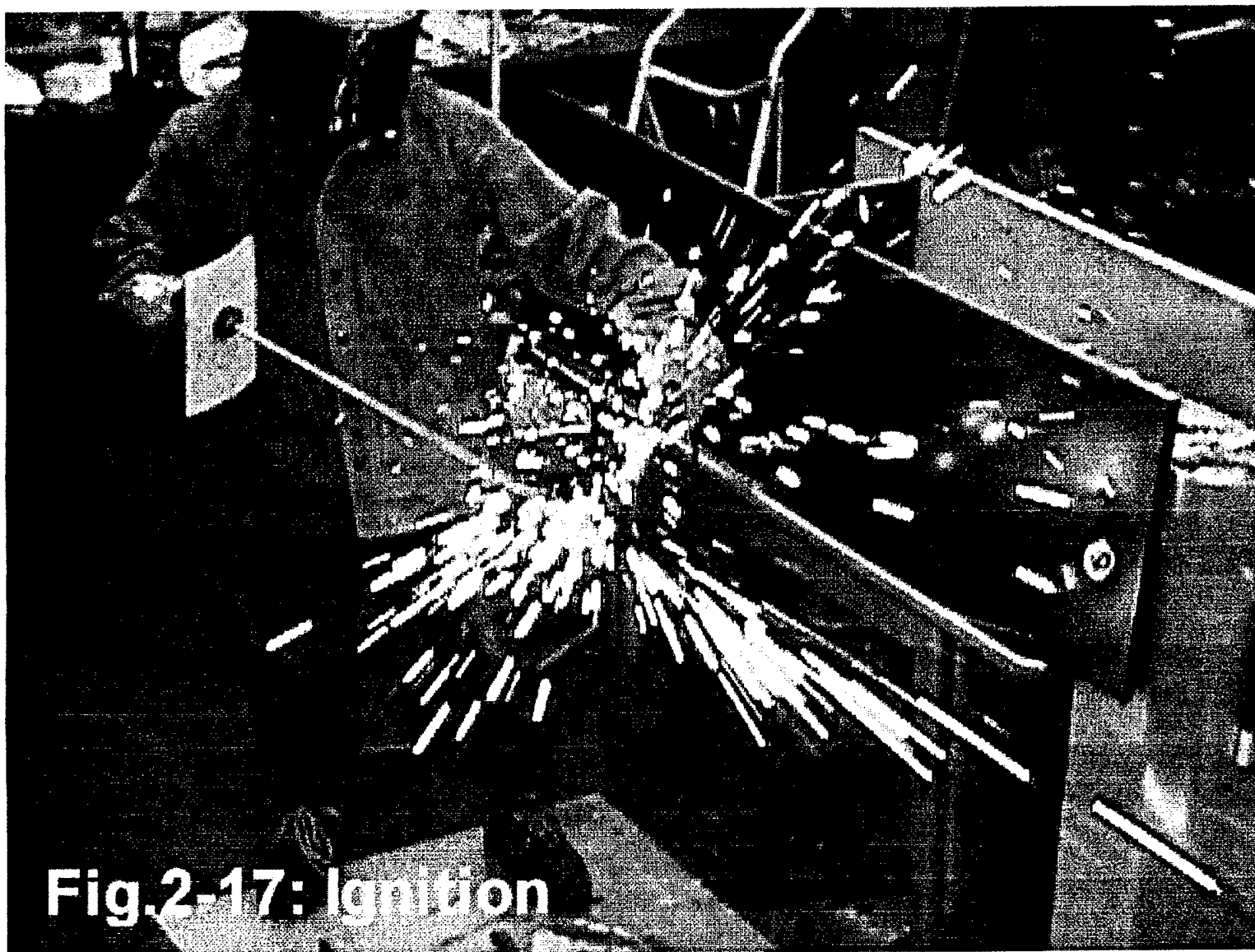
**1 IN**











**Fig.2-17: Ignition**

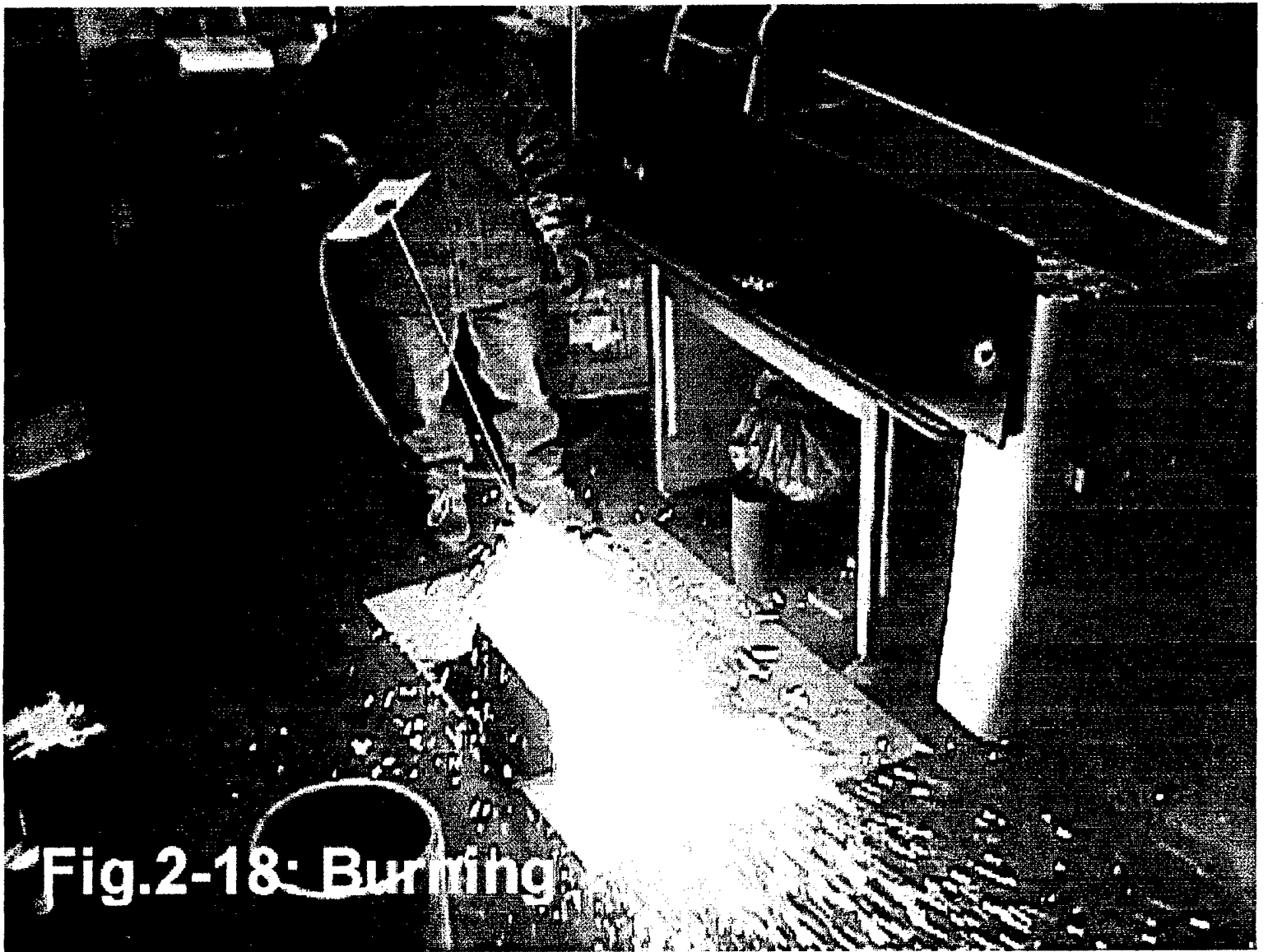


Fig.2-18: Burning

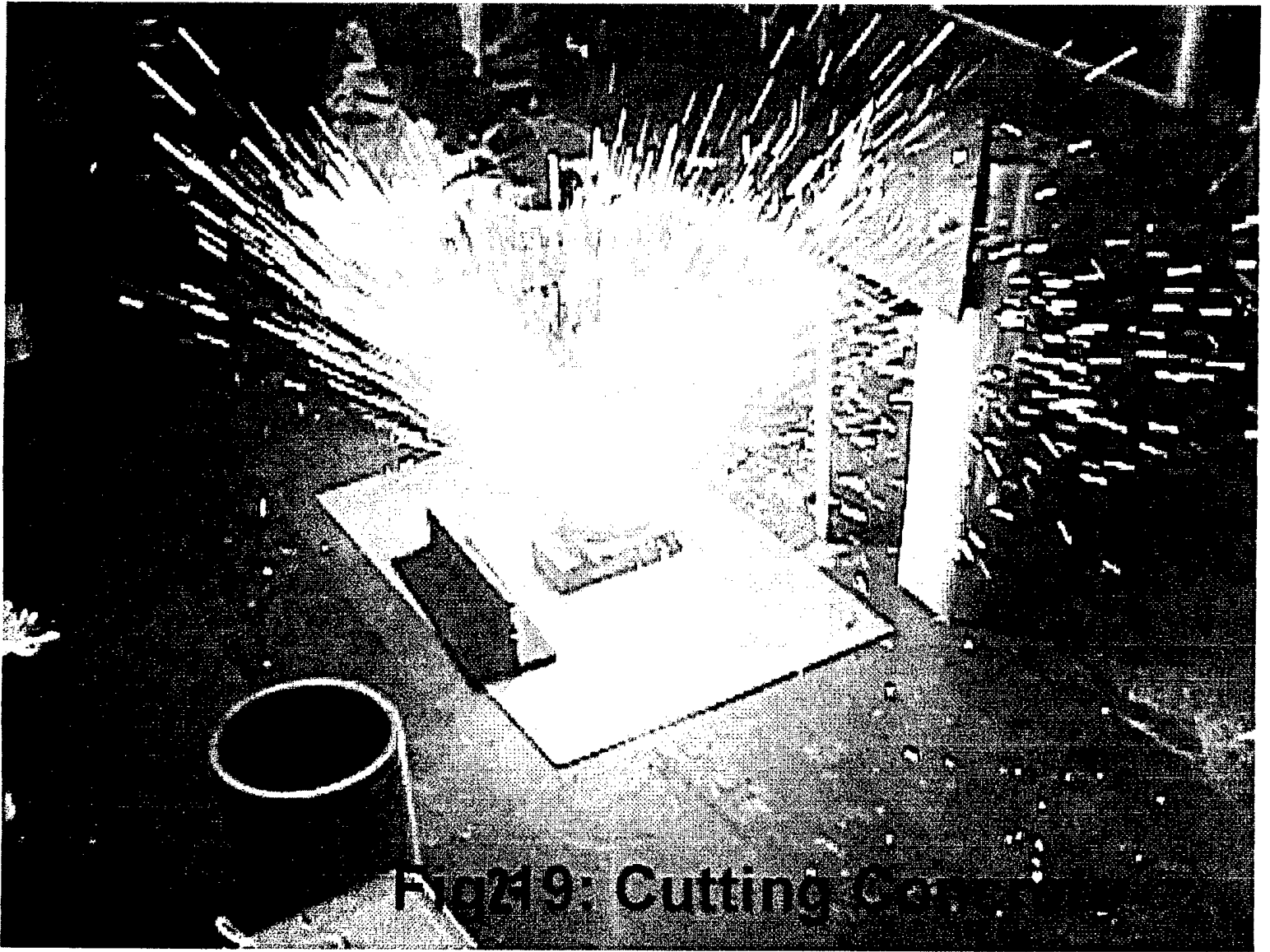


Fig219: Cutting Operation

### **III.4.1.Preparation of reinforced concrete sample**

The concrete mix (Quikrete, No.1101) and rebars were purchased from a local store. The concrete mix consists of gravel, sand, and Portland cement. The concrete plates were made according to standard procedures. They were cured for 22 days and have a compressive strength of about 3500 psi. The diameter of the rebar used was 0.52 inch (1.33 cm). Three types of concrete samples were made: concrete plate without rebar, reinforced concrete plate with single rebar, and reinforced concrete plate with rectangular mesh of rebars.

### **III.4.2.Cutting of reinforced concrete plates by the oxy lance**

The oxy lance and burning rod of 3/8" were used in the cutting experiments. The oxygen used has a purity of 99.6% and the pressure was set to 60 psi. Cutting experiments with various concrete plates of different thickness and different rebar arrangements were performed. The results are displayed in Figs.3.1-3.4. Figs.3.1a and b show the piercing of a plain (non-reinforced) concrete plate. The plate cracked and fall apart to several pieces during the piercing operation. Evidently, the non-uniform thermal stress, caused by the high temperature at the piercing point, and the high temperature gradient in the sample were responsible for the thermal destruction. Figs.3.2a and b and 3.3a and b display the pierced reinforced plates with single rebar. Figs.3.4a and b illustrate the results of piercing operation on a reinforced concrete plate with a rebar mesh. The lance penetrated the concrete plate at the cross section of two rebars. The conditions of the experiment are presented in the corresponding figures. The cutting time was in the range of 10 to 27 seconds. It is extremely interesting to notice that the piercing of the thicker reinforced concrete plate (Fig.3.4a and b) with rebar mesh took less time than the thinner one. Apparently the burning of the rebars embedded in the sample enhanced the melting of the concrete. This strategy must be systematically tested in future. Evidently the operator, once he discovered during the piercing operation a rebar, should continue in the rebar direction. The iron fuel will safely burn in the flame and will save the material in the lance.

### **III.4.3.Cutting by oxy-gasoline torch**

The cutting of the concrete plate by the oxy-gasoline torch was performed. Tip # 4 was used and the oxygen (99.6% O<sub>2</sub>) pressure was set at 50 psi. The flame can melt the surface but the lava cannot be easily removed. After piercing by the flame for over 3 minutes, only a shallow layer of the plate was removed.

To enhance the cutting power of the flame, chloroform ( $\text{CHCl}_3$ ) was mixed to the gasoline. Gasoline with 2%, 5%, and 10% of chloroform was tested. The results showed that the lava was white ash and could be easily removed after cooling. Higher chloroform content caused problems of torch ignition. Figs.3.5a and b and 3.6a and b show the difference of the lava type.

#### **III.4.4.Effect of oxygen purity on the speed of steel plate cutting**

Oxygen purity of 99.5% and 99.99% was tested for the steel plate cutting. The prices of the 99.5% and 99.99% oxygen are \$47 and \$243.9 per "T" cylinder, respectively. The oxy-gasoline torch and tip #4 were used. The oxygen pressure was set to 50 psi. The steel plates of thickness 0.3" and 0.5" were cut. The differences of the cutting speeds were not obvious. Therefore, oxygen purity higher than 99.5% is not necessary for the cutting. The dependence of cutting speed on concentration of oxygen is presented in Fig.3.7. It is obvious that the purity of oxygen will affect the cutting speed in almost exponential way and that for very fast operation the purity under 99.5% cannot be recommended.

#### **III.5.Case studies of the portable cutting systems**

##### **Case 1: Cutting of a man size hole in a steel plate**

The purpose is to quickly cut a hole in a 1" thick steel plate big enough for a man to pass through.

Oxy-gasoline torch with tip #4 is used.

The hole should have diameter=25" .

We must cut:  $\text{Length} = \pi d_t = 78.5$  inches.

The cutting speed,  $v$ , measured in our experiments:  $v = 0.25$  inch/second.

Time for completing the job:  $t = 5.2$  minutes

The amount of oxygen required:  $V = 32$   $\text{cf}^3$

The weight,  $W$ , of a 16  $\text{cf}^3$  cylinder full of oxygen:  $W = 16$  lbs.

Two  $\text{O}_2$  cylinders: 32 lbs.

Gasoline (0.5 gallon tank): 10 lbs.

Handle & tip: ~ 3 lbs.

Total weight of the cutting system is 45 lbs.:

## **Case 2: Cutting of rebar grid.**

Suppose that the reinforced concrete wall has been demolished by other means (for example by a flying disk impact) and that the remaining twisted 1/2" rebar grid has to be cut. The distance between the rebars in the grid is 20 cm and therefore 10 rebars must be cut to make a "31.5 inch by 23.6 inch" hole, which is big enough for a man to pass. Based on our data the job can be done in 2 minutes. The oxygen consumption required is 12.4 cf<sup>3</sup> so that one small oxygen cylinder is sufficient.

We need:

One O <sub>2</sub> cylinder:	16 lbs.
Gasoline (0.5 gallon tank):	10 lbs.
Handle & tip:	~ 3 lb.

Total weight of the cutting system is 29 lbs.

## **Case 3: Cutting of a man size hole in a reinforced concrete plate**

The task is to cut a man size hole of diameter = 25 inches in a reinforced concrete plate of 2.36 inch thickness. This job can be done by oxy-lance. The lance can pierce a hole of 2" diameter in 25 seconds. The circumference of the man size hole is 78.5 inches. We can pierce 26 holes evenly distributed along the circle of the man size hole. The space between two pierced holes is 1", however the material has been heavily damaged by the piercing action on the adjacent holes. Therefore the entire disk can be easily knocked out manually or by a small charge of plastic explosive. It takes 10.8 minutes to finish the piercing. The total amount of oxygen needed is 43.2 cf<sup>3</sup>. Therefore three small oxygen cylinders (each contains 16 cf<sup>3</sup> O<sub>2</sub>) are sufficient for the job.

We need:

Handle and burning rod:	3 lbs.
Three oxygen cylinders:	48 lbs.

Total weight of the cutting system is 51 lbs.

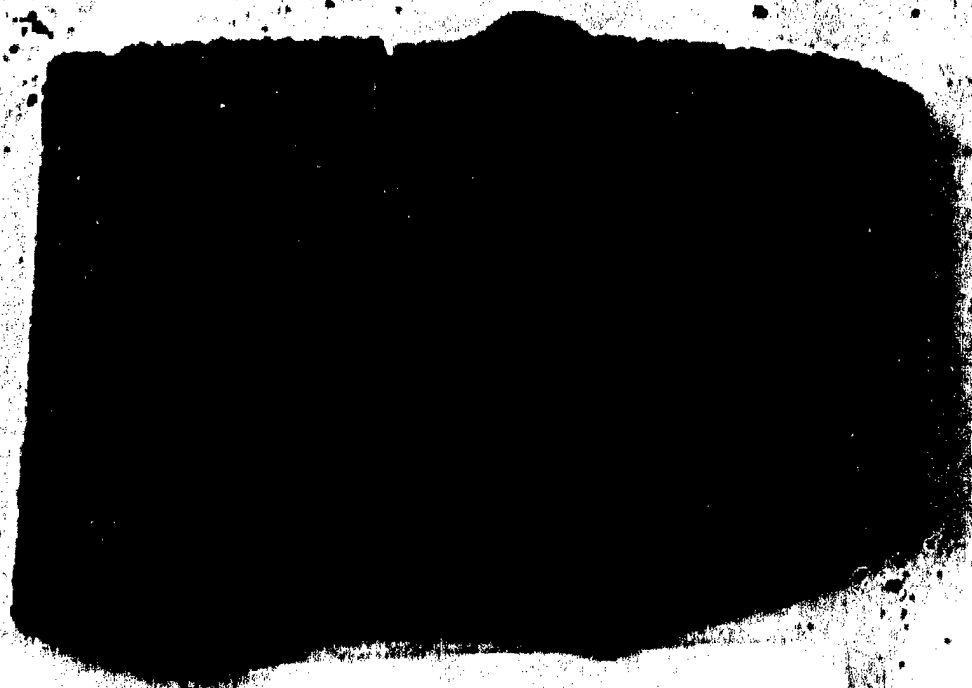
## **III.6. Comparison of oxy-lance and oxy-gasoline cutting torches**

### **III.6.1. Cutting performance**

For cutting thick steel pieces, the oxy-lance is more powerful than oxy-gasoline torch since it operates at higher temperature. It requires virtually little pre-heating time before it cuts and it can reach deeper to the workpiece. Therefore, for piercing or cutting thick steel plates oxy-lance seems to be superior. For cutting steel of thickness less than 1 inch, oxy-gasoline torch gives a continuous cutting edge and a

Time=10s

Cutting Rod: 3/8"



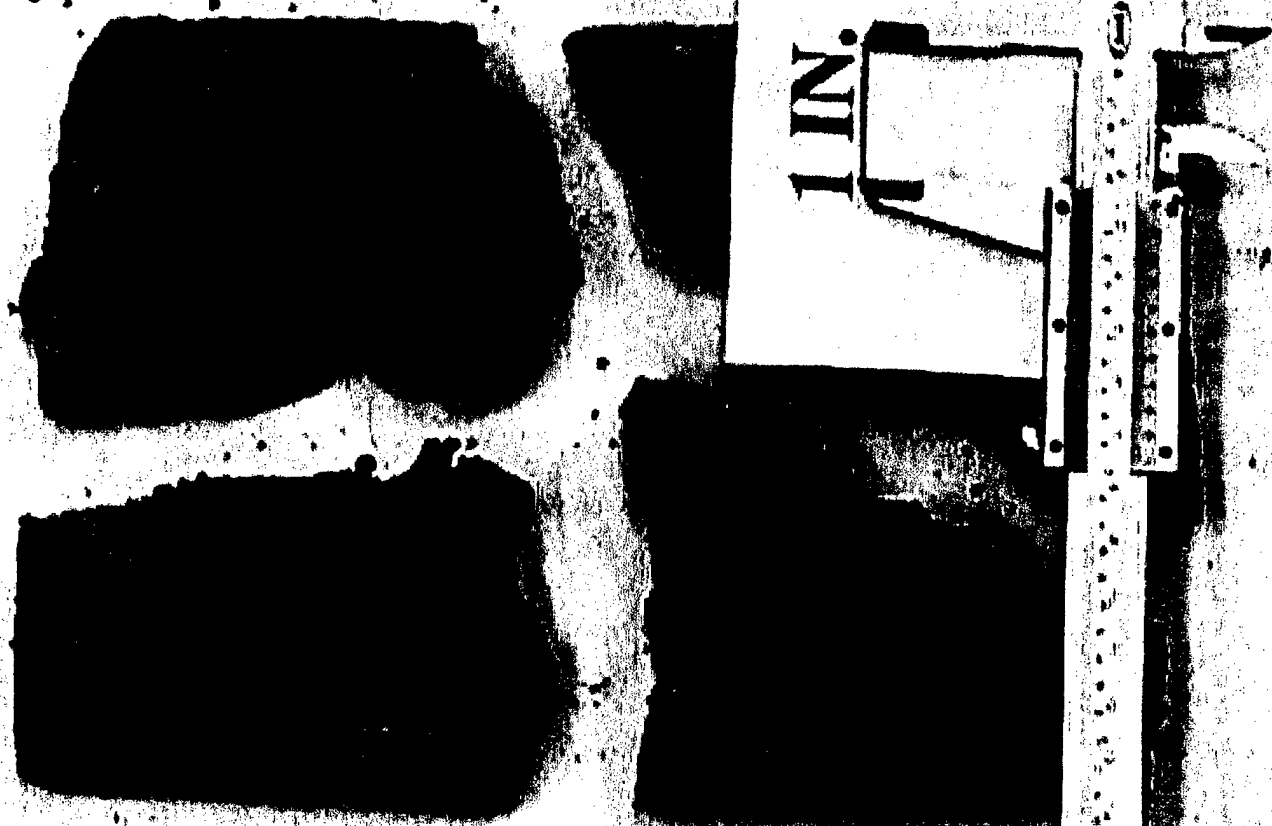
Thick.=0.67"

1 IN.

Fig.3.1a Concrete Plate

Thick.=0.67"

Cutting Rod: 3/8"



Time=10s

Fig.3-1b Concrete Plate



**Thick.=1.34"**

**Cutting Rod:3/8"**



**Time=23s**

**Fig.3-2a Reinforced Concrete Plate**

**Thick.=1.34"**

**Cutting Rod:3/8"**

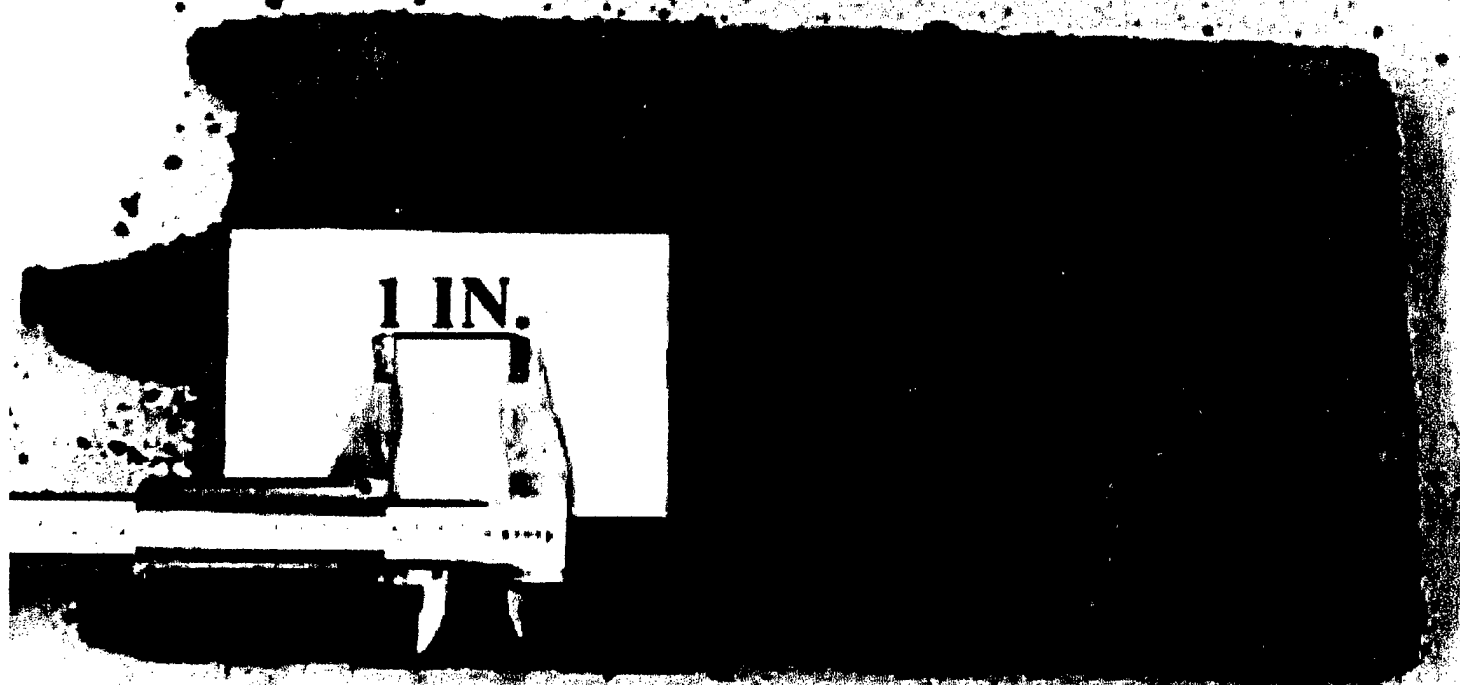
**Time=23s**

**1 IN.**

**Fig.3-2b Reinforced Concrete Plate**

**Thick.=1.65"**

**Cutting Rod:3/8"**



**Time=27s**

**Fig.3-3a Reinforced Concrete Plate**

# **Fig.3-3b Reinforced Concrete Plate**

**Thick.=1.65"**

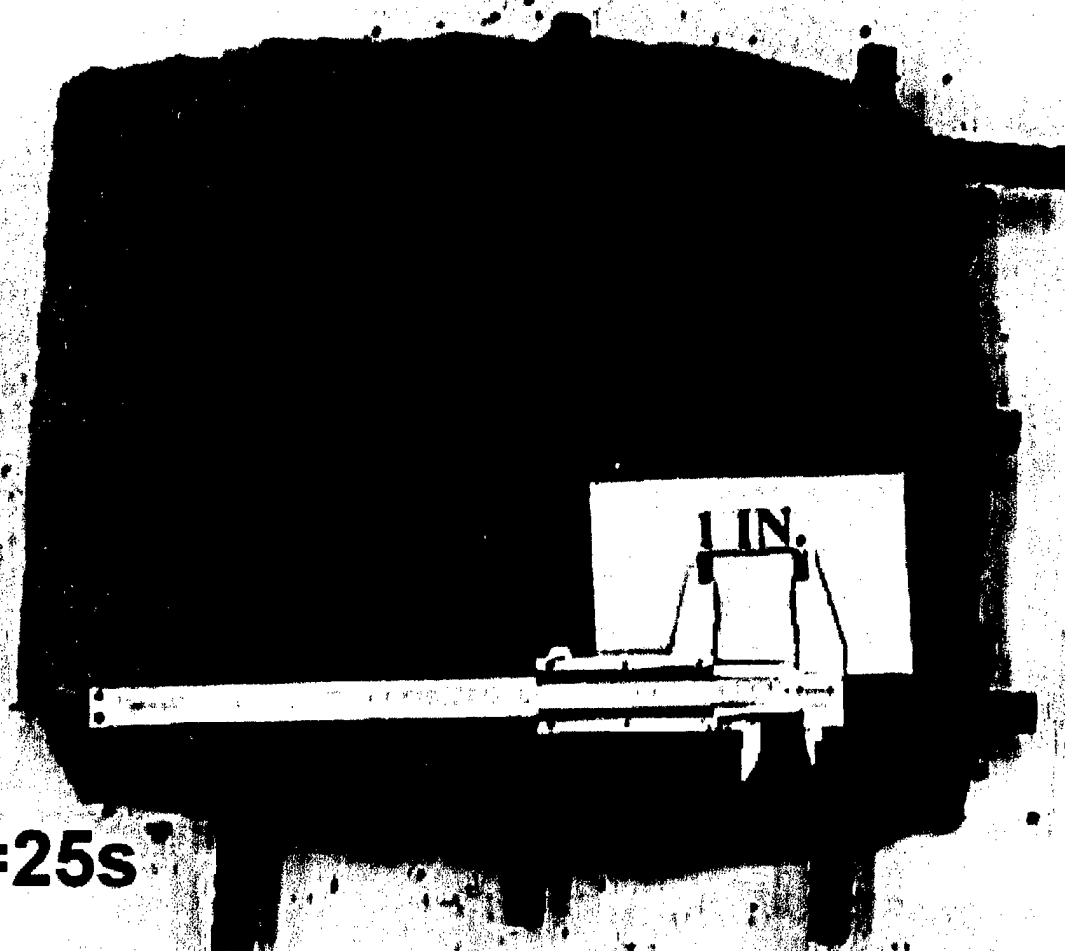
**Time=27s**

**Cutting Rod:3/8"**



**Thick.=2.36"**

**Cutting Rod:3/8"**



**Time=25s**

**.Fig.3-4a.Reinforced Concrete Plate**

**Thick.=2.36"**

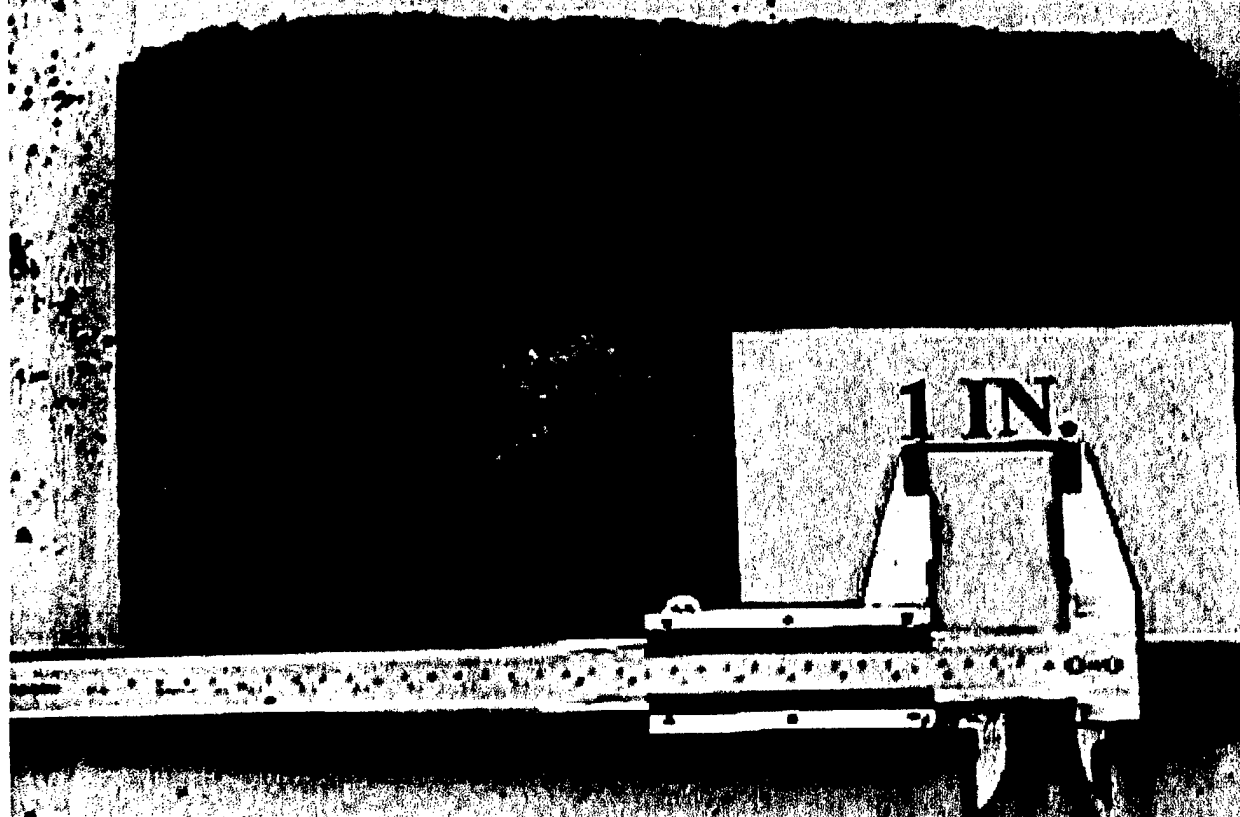
**Cutting Rod:3/8"**

**Time=25s**



**Concrete Plate**

**Thick.=0,63"      Oxy-gasoline Torch**



**Gasoline+10%vol%CHCl<sub>3</sub>**

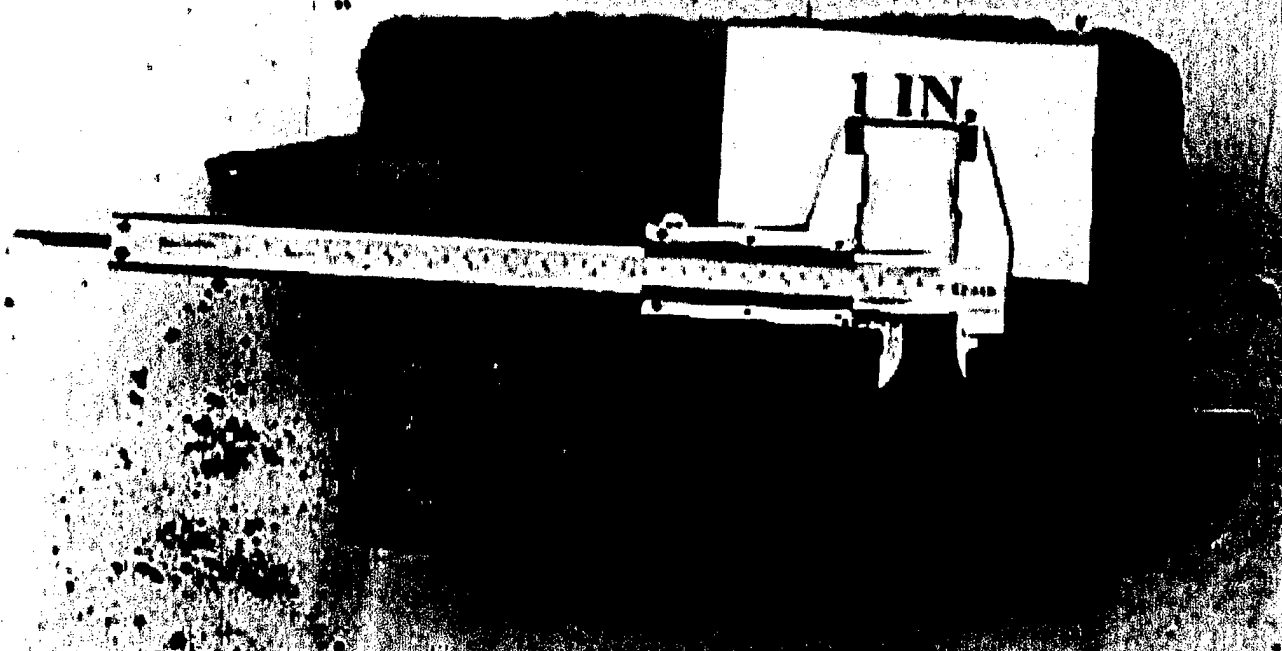
**Fig.3-5a Concrete Plate**





**Thick.=0.63"**

**Oxy-gasoline Torch**



**Pure Gasoline**

**Fig.3-6a Concrete Plate**

**Thick.=0.63"**

**Oil-gasoline**

**Pure Gasoline**

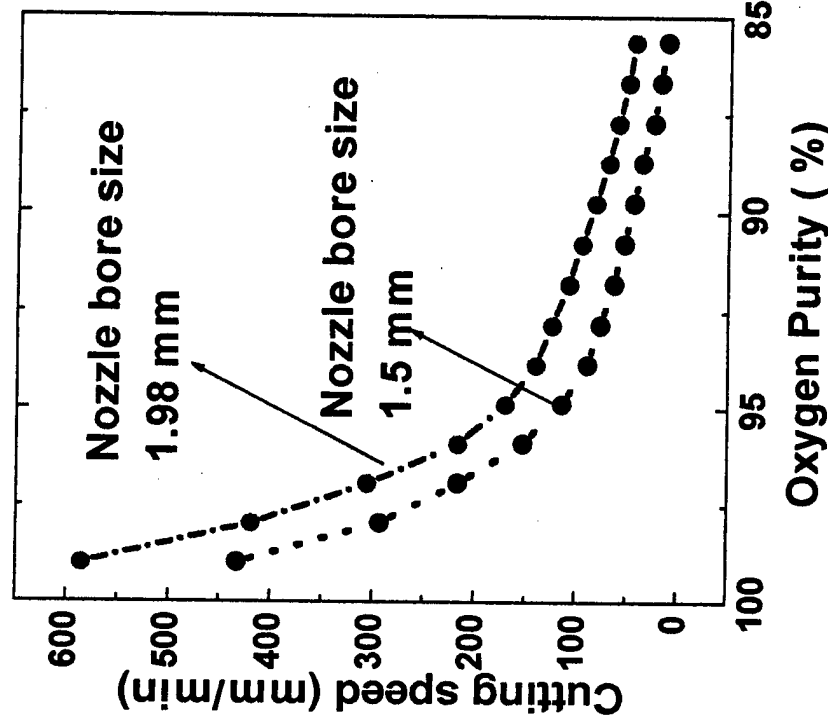
**Fig.3-6b Concrete Plate**

Fig. 3.7.

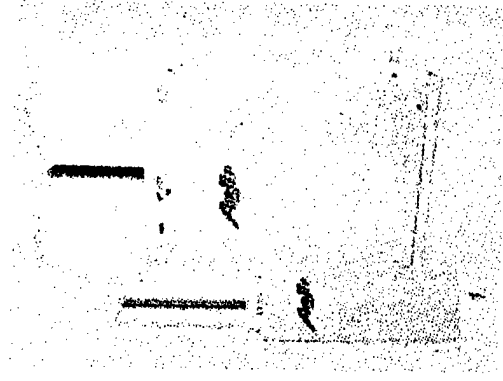
SBIR Project - Ultra-fast Portable Metallic/Concrete Plate Cutting

CMP

## OXYGEN PURITY IMPERATIVE



O<sub>2</sub> 99.6%, \$ 47/cylinder  
recommended by us  
O<sub>2</sub> 99.8%, \$ 141/cylinder  
O<sub>2</sub> 99.99% not necessary



complete oxidation of metal so the splatter is mild and not so hot. Therefore, oxy-gasoline torch it is more user friendly than the oxy-lance torch.

The oxygen consumption for oxy-lance is 240 cf<sup>3</sup>/hour (~6.8 m<sup>3</sup>/hour). This amount is close to that of the oxy-gasoline torch when tip #3 is used (275 cf<sup>3</sup>/hour for tip #3; 115 cf<sup>3</sup>/hour for tip #1; and 370 cf<sup>3</sup>/hour for tip #4).

The oxy-lance uses only oxygen and a metal rod and does not need any liquid or gaseous fuel for cutting. However, a battery is necessary for the ignition of the torch.

### **III.7. Scale-down of the torch Systems**

It is obvious that the scale-down of the oxygen system is the key to make both the oxygasoline and the oxy-lance torch systems portable. Three possible ways are discussed as follows:

#### **(a) use a small oxygen gas cylinder**

The smallest one, which holds 16 cf<sup>3</sup> of oxygen, is commercially available. The total weight of the cylinder is 16 lbs. For oxygasoline torch, this amount of oxygen is enough for the torch to work 8.5 minutes with #1 tip or 2.6 minutes with #4 tip. Based on the data we have obtained, the 16 cf<sup>3</sup> of oxygen is enough to cut 110 inches of steel plate of 0.14 inch thickness by #1 tip or 42.4 inches of a plate of 1.02 inch thickness by #4 tip. For oxy-lance cutting torch, the amount is sufficient for burning 3 pieces of 3/8"(D)x18"(L) burning bars, which can penetrate 15 holes on a 2-4" thick concrete.

#### **(b) Use liquid oxygen**

Oxygen in liquid form can be transported in a small container with high oxygen storage density. However, two things hinder its application on a small scale: i) heat source is needed for vaporization of the liquid oxygen (-182.96°C). The Mills Welding & Specialty Gases, Inc. designed a system using liquid oxygen for cutting & welding. They use a built-in vaporizer to absorb heat from ambient air. The smallest system they designed has a total weight of over 100 lbs. Further scaling down of the system is difficult since the size of the vaporizer has to be maintained to guarantee flow rate required by the torch. This is a truly clumsy solution and we would never consider it in future. The German technology is more elegant, they have designed a system where liquid oxygen is directly injected in the flame. According to their data an increase of factor two can be achieved in cutting speed

ii) liquid oxygen in the tank will evaporate in a few weeks. Therefore oxygen must be produced on spot if a very flexible operation ought to be accomplished.

### **(c) Oxygen candle**

Chlorates and perchlorates of lithium, sodium, and potassium evolve oxygen when heated. These salts can be compounded with a fuel to form a chlorate-based candle that produces oxygen by a continuous decomposition of the chlorate. Chlorate candle possesses high oxygen storage density and high stability (can be stored for 20 years). The commercially available oxygen candle is \$453 each. It provides oxygen for the breathing of a person for 15 minutes. The pressure and the rate of oxygen generation are not enough for cutting purpose.

For cutting purpose, it is not necessary to remove traces of impurities such as chlorine as is required for medical purpose. But it is important to get high rate of oxygen generation. Therefore, we decided to develop a cheap, simple candle, which generates oxygen at a flow rate of 4 cf<sup>3</sup>/min and a pressure up to 80 psi. Sodium chlorate was chosen as the major material and iron as the fuel for our experiments. A small amount of catalyst such as BaO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, or CoO was also used to decrease the decomposition temperature. DT/TG analyses were performed. As a first attempt, a candle of 12% Fe<sub>2</sub>O<sub>3</sub>, 12% Fe, and 76% NaClO<sub>3</sub> was made and ignited by flame. The chlorate continuously decomposed to completion and oxygen was produced.

### **III.8. Experimental work on the oxygen generation candle**

A chlorate candle is an efficient oxygen source on a weight and volume basis. The only commercially available chlorate candle is manufactured by SCOTT AVIATON. The candle generates oxygen at a flow rate of 4-6 liters/min and it lasts for 15 minutes. The flow rate is 20 times less than the 112 liters/min, which is required by the cutting torch. We had discussions with the company on the possibility of supplying bigger candles. They showed little interest. Therefore we decided to develop the candle on our own. The diameter of the candle necessary for supplying 112 liters/min estimated to be 18 cm. It will be not practical to prepare such a candle, in the 2nd Phase of SBIR we will design a regular packed bed filled by granules of the reacting mixture. Such units can guarantee very large flow rate of oxygen generated.

The following problems in the scale-up of the candle have to be solved: (a) the ignition of the candle; (b) the control of the temperature increase from the transient

heat of reaction accumulation during the burning of the candle; and (c) to keep the decomposition reaction at a constant rate.

### **III.8.1 Using rich-Fe-layer for ignition**

The ignition of a big cold candle requires a high initial energy from the ignition layer.

In our experiments,  $\text{NaClO}_3$  (99+%, granular) was the major component in the candle. Fe (6-10 micron, 99.5%) was incorporated as a fuel to supply the heat for decomposition of  $\text{NaClO}_3$  when oxidized.  $\text{Fe}_2\text{O}_3$  (<5 micron, 99+%) was added as a catalyst. The  $\text{NaClO}_3$  was first milled to -50 mesh together with Fe and  $\text{Fe}_2\text{O}_3$ . The powder mixture of (81%  $\text{NaClO}_3$ )+(7% Fe)+(12%  $\text{Fe}_2\text{O}_3$ ) was pressed to a candle of diameter of 1.12 inches (Figs.2.20a and b). The Fe rich layer consisted of 68%  $\text{NaClO}_3$ , 15-20% Fe and 12-15%  $\text{Fe}_2\text{O}_3$ . The candle was insulated by glass wool. Ignition was realized by heating the rich Fe layer (10 g) by an electrical induction coil.

The minimum amount of the rich Fe layer to achieve ignition is 10 grams with 15-20% Fe. Experimental results showed that the burning of the rich Fe layer after ignition resulted in a rapid decomposition of sodium chlorate and a high rate of  $\text{O}_2$  generation.

### **III.8.2. Measurement of flow rate**

To measure the flow rate of the oxygen generated, the candle was placed into a sealed vessel. The ignition was done as described above. An orifice flow meter was used to measure the flow rate. The oxygen generation flow rates of 3 samples with different catalyst ( $\text{Fe}_2\text{O}_3$ ) concentrations were recorded in Figures 2.21-2.23.

From the results we can see that without the catalyst ( $\text{Fe}_2\text{O}_3$ ), the oxygen generation rate increased gradually to the maximum and then decreased rapidly to zero. By adding 1.7% of  $\text{Fe}_2\text{O}_3$  to the candle, the peak value decreased from 11.5 liters/min to 8.8 liters/min. When 10%  $\text{Fe}_2\text{O}_3$  was added, the peak value was further reduced to 7 liters/min and the flow rate between 4 and 7 liters/min lasted for a longer time.

### **III.9. Preparation on new energetic fuel for oxygasoline cutting**

In our oxy-cutting experiments described above we have used as fuel high octane gasoline. However, it is possible to increase the energy of the liquid and temperature of the flame by producing slurry of ultra-fine metals, in particular



$\text{NaClO}_3 + \text{Fe}_2\text{O}_3 + \text{iron powder}$  by pressing

**Fig.2-20a: Sodium Chlorate Candle**

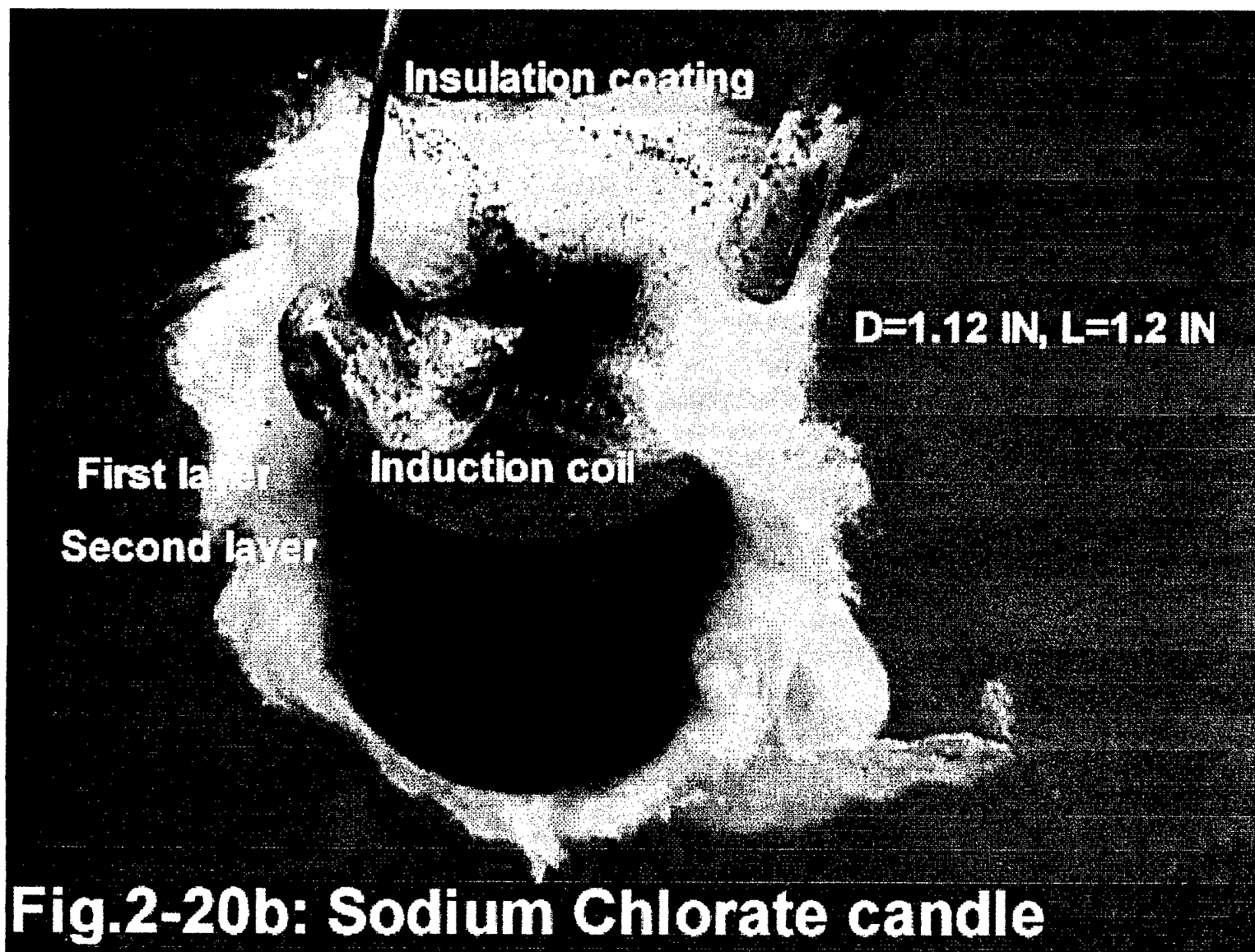




Fig.2-21

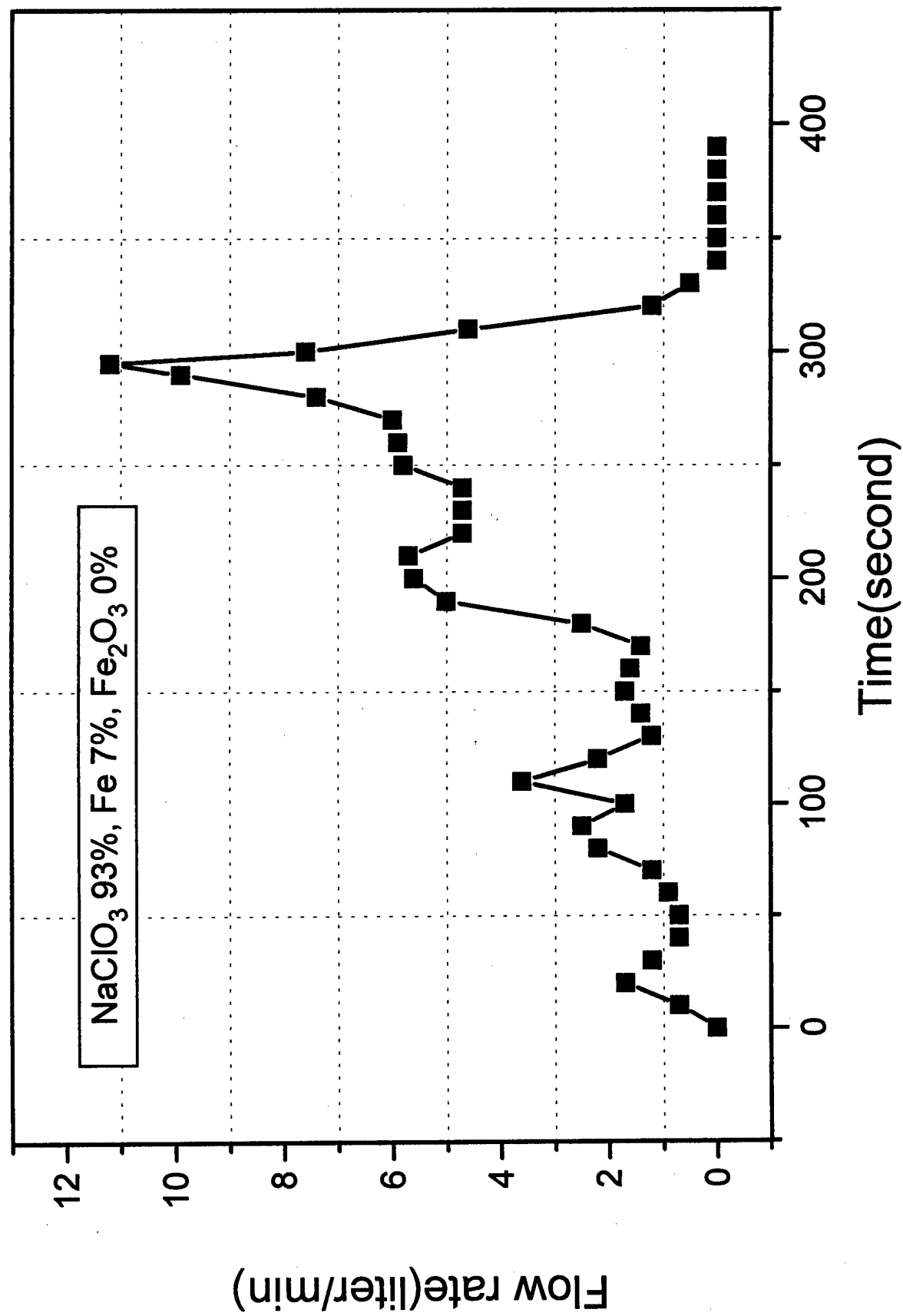


Fig.2-22

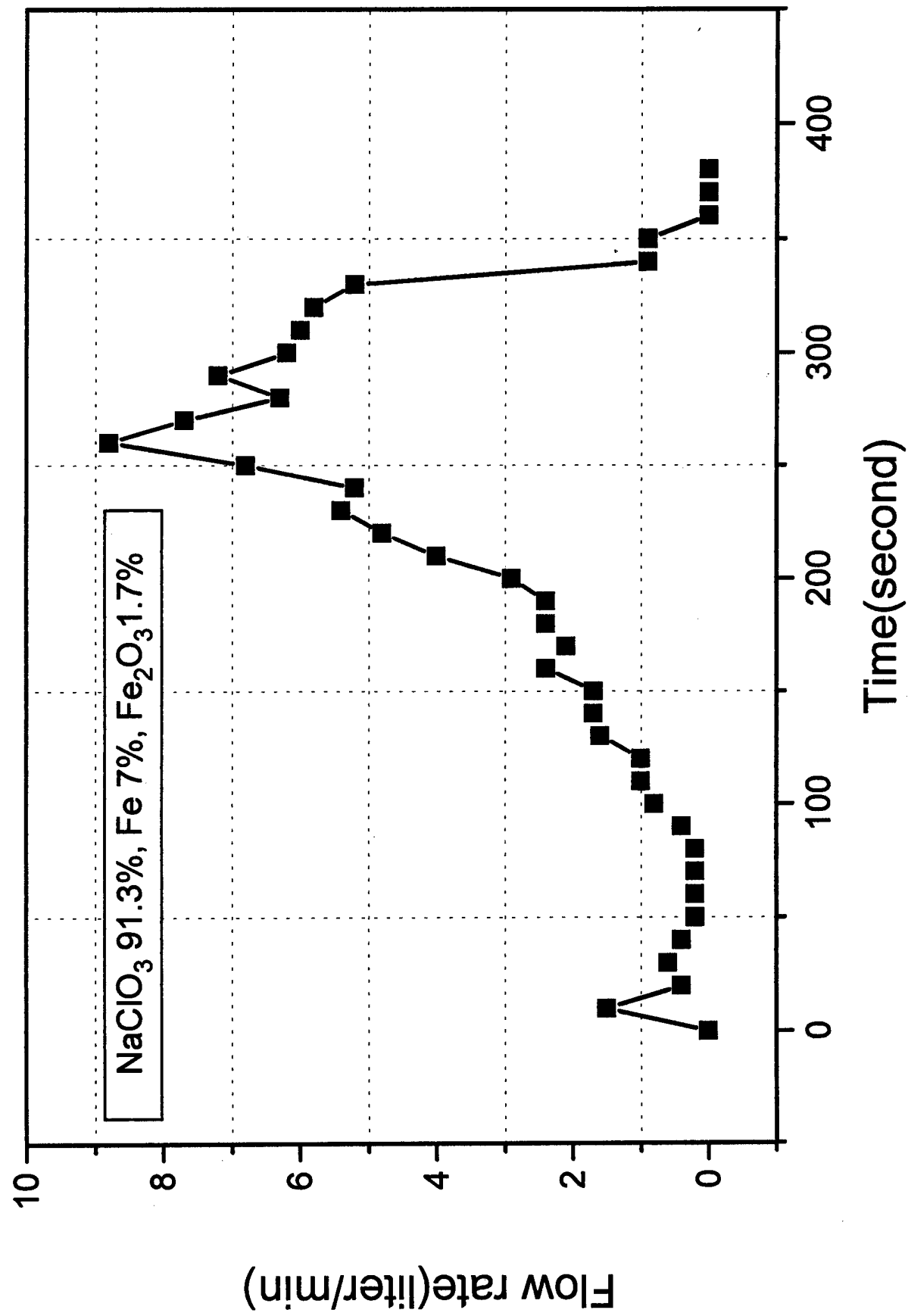
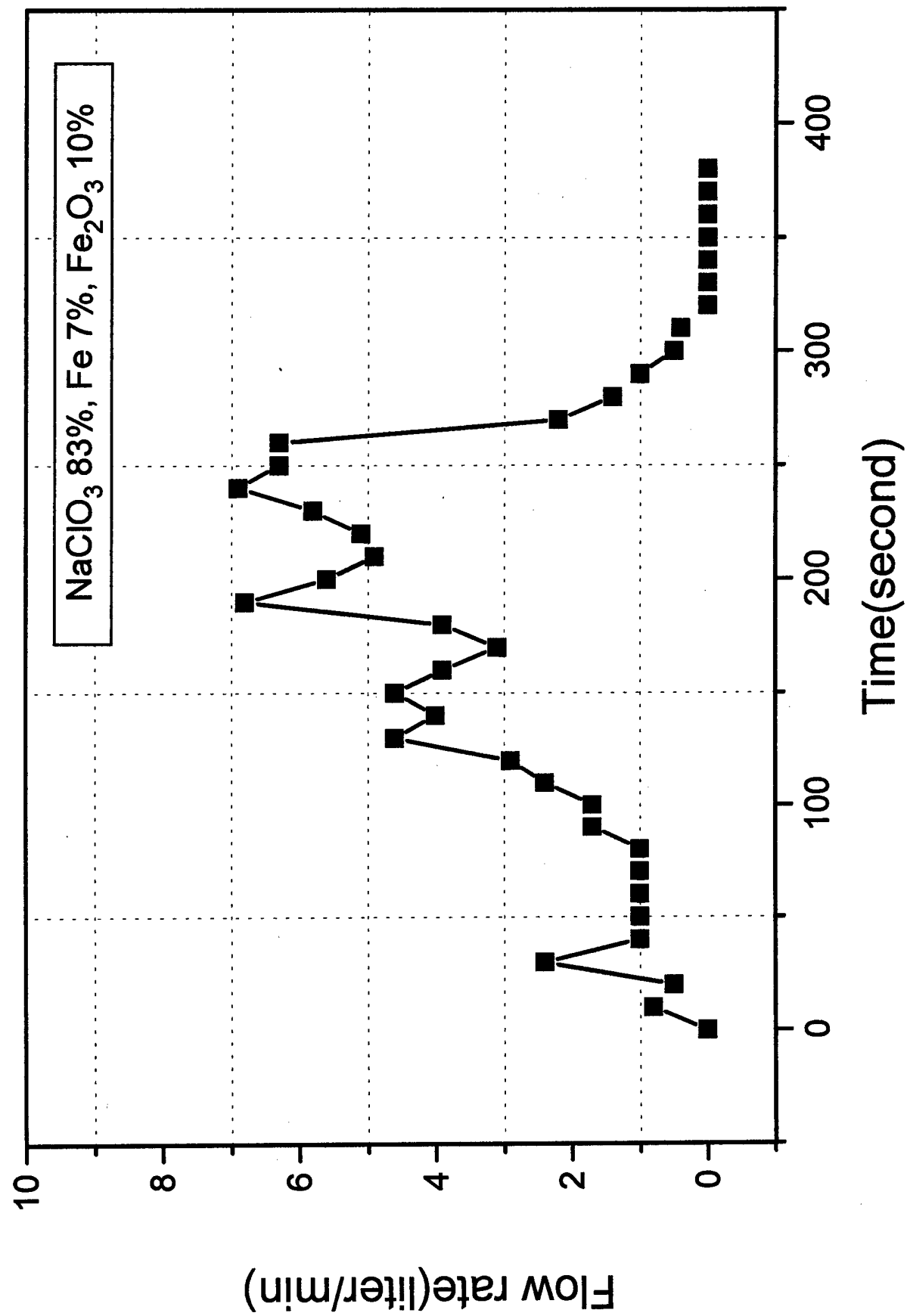


Fig.2-23

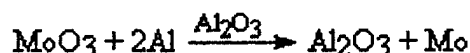


aluminum in liquid hydrocarbons. This slurry can be kept in the gasoline tank and handled as liquid gasoline. The slurry has been produced by a proprietary process developed by Ceramics and Materials Processing Company and contains 10-55% of ultra-fine aluminum suspended in a hydrocarbon. The metallic colloidal particles suspended in the gasoline feature surface area of 15-30 m<sup>2</sup>/g. Based on our pyrometric measurements the temperature of the flame, produced by combustion of this slurry can increase to 3,200-3500<sup>0</sup>C. This slurry makes it possible to cut concrete by using the oxo-fuel technology. Systematic investigation of cutting characteristics of iron plates and reinforced concrete will be studied in the Phase II.

### III.10. Development of new energetic fuels for SHS cutter.

The objective of this experimental research is to measure combustion front velocities in the following reacting systems:

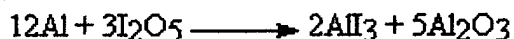
1) Molybdenum oxide – Aluminum System



2) Titanium – Boron System

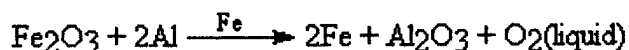


3) Iodine Pentaoxide - Aluminum System



In addition, iron oxide - aluminum – iron system is studied to determine how the overall reaction behaves under an oxygen-bearing environment. The focus of this study is on a possible application of this system to perform localized melting of steel structures. It was decided to dilute the iron oxide-aluminum system with iron metal in order to make the thermite system more controllable. Without dilution the mixture upon ignition was partially expelled from the container.

4) Iron oxide – Aluminum – Iron System



## Experimental Setup

*Thermocouple preparation:* Each thermocouple was prepared from tungsten-rhenium wires (5 wt% and 26 wt%) with diameter 0.003", see Fig.4.1. Both wires were joined using arc-welding equipment. Each thermocouple was then coated with a boron nitride paste (except of the tip of the thermocouple) to provide an oxidation resistant barrier. After eight hours of proper drying of the boron-nitride coating, thermocouples were connected to the data acquisition system using CX extension wires. The thermocouples were placed in the specified axial position in a graphite boat. The wires were introduced through the two-hole alumina tube in order to eliminate any electrical disturbances. Prior to the ignition, the thermocouples were tested to ensure reliable data collection. The experimental setup is shown in Figure 4.2.

*Refractory Graphite Boat:* The refractory boat that houses the molybdenum, titanium, and iodine systems was constructed using refractory graphite, see Fig.4.3.

*Iron oxide – Aluminum – Iron System:* The bottomless clay crucible (see Fig.4.4) was placed onto the mild steel plate. A stoichiometric mixture of iron oxide and aluminum with 15 wt% of iron powder ( $d_{avg}=5 \mu m$ ) was then placed into the crucible and a valley made at the bottom. This central hole was intended for a possible direct channel for liquid oxygen into the hot steel plate. The resistively heated molybdenum wire was used to ignite a thermite system.

## Experimental

The **Molybdenum Oxide – Aluminum System** was explored using the graphite boat, variable voltage transformer, and shielding. Data acquisition was achieved using Strawberry Tree™ software. The sub-micron  $MoO_3$  (sublimed) was purchased from the Cyprus Company and the aluminum from the Reynold's Company with average particle size of 5 microns. Each sample consisted of the proper dilution of reactants by using the diluent aluminum oxide ( $Al_2O_3$ ). Four samples were prepared consisting of 0%, 10%, 20%, and 30% by weight diluent ( $Al_2O_3$ ). The aluminum and aluminum oxide were combined and mixed well for 2 hours. Once mixing ceased, the mixture was combined with molybdenum oxide and put through a 200 mesh sieve ten times to ensure adequate mixing. Typically, twenty-five grams of reaction mixture were prepared at one time to satisfy safety and to allow better mixing of key reactants. Fifty grams of the mixture was then



Figure 1. Welded rhenium-tungsten thermocouple coated with boron nitride

#### SCHEMATIC OF THE EXPERIMENTAL SET-UP

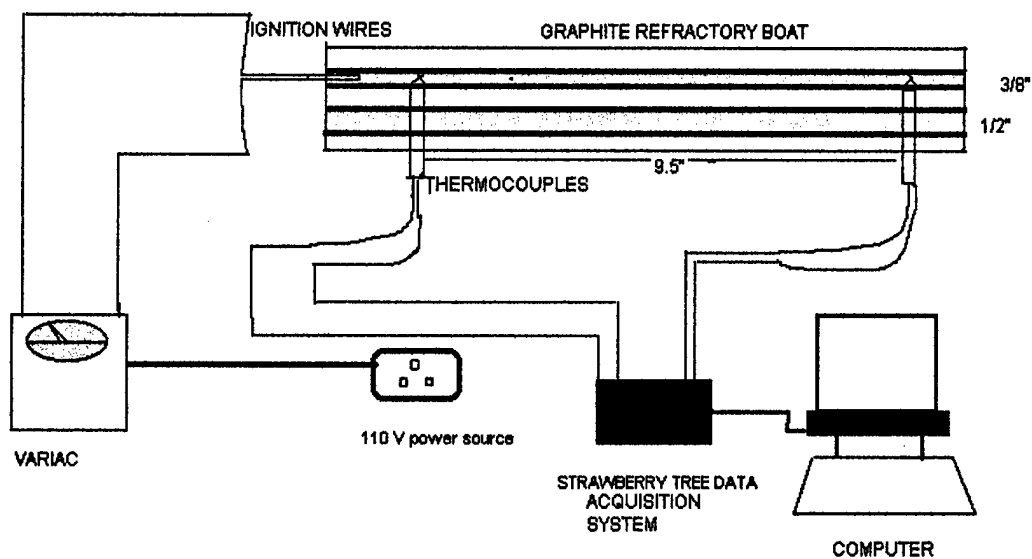


Figure 2. Schematic of the experimental setup.



Figure 3. Graphite refractory boat

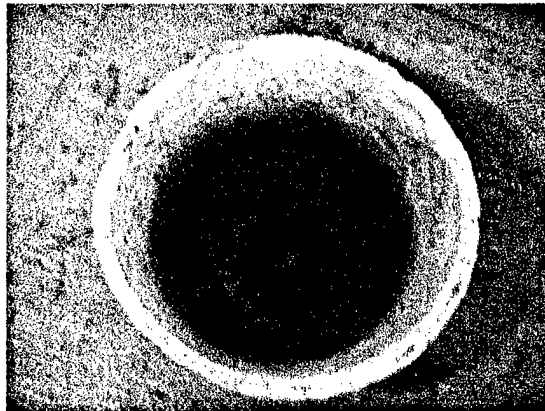


Figure 4. Ceramic crucible containing the 15% by weight Fe diluent and stoichiometric mixture of iron oxide and aluminum.

carefully placed in the graphite boat using a spatula with a slight densification. Once packing of the boat was completed, all connections were protected with refractory insulation to prevent any destruction to the wiring and equipment. Shielding was also necessary to protect the experimenters, equipment, and camera from any sparking and heat liberated from the reaction. The molybdenum ignition wire was then connected directly to a variable voltage transformer where approximately 10 volts was supplied to the Mo-ignition wire. Simultaneously the data acquisition system was enabled to record temperature responses from two rhenium-tungsten thermocouples. Once completion of the combustion process was evident, the data acquisition system was disabled.

Up to the date the experimental data are summarized in the Table 1.

Table 1. Propagation characteristics in MoO<sub>3</sub>-Al system.

COMPOSITION [wt% Al <sub>2</sub> O <sub>3</sub> ]	Combustion front velocity [m/s]	Combustion temperature [°C]	Observations
0.0	4.0  (more experiments will be conducted using new data acquisition software)	2200	Recorded temperatures were relatively low because the majority of the material was sublimed (no contact with the product). The relatively small amount of the products was present at the bottom of the combustion channel. Dense smoke was generated during the combustion.
20.0	0.214	2700	A significant portion of the products was expelled from the channel. Significantly less smoke generated during the combustion process.
30.0	0.03	2100	Relatively slow process. Only insignificant sparking was generated during the propagation in the channel.

The adiabatic temperatures calculated using the HSC software from the Outokumpu Company are presented below. The data generated for dilutions below

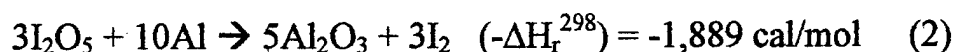
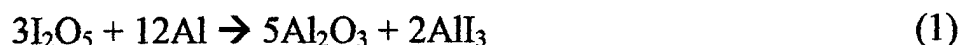


15 wt% might be less accurate due to the uncertainty of thermophysical data (see Figure 4.5.).

The **Titanium – Boron System** was investigated by preparing forty-five grams of titanium-boron mixture (Ti-2B). The titanium was purchased from the RMI Titanium Company with -325 mesh size ( $d_{avg}=18 \text{ :m}$ ) and 99% purity. The boron was purchased from SB Chemicals Ltd. with 96% purity ( $d_{avg}< 1 \text{ :m}$ ). Once these two components were combined, they were put through a 200 mesh sieve several times to ensure complete mixing. Approximately 5 grams of 20% by weight  $\text{Al}_2\text{O}_3$  molybdenum oxide mixture was used as the ignition mixture for that system. The titanium – boron mixture was then placed in the graphite refractory boat with slight packing. The system was ignited in a similar manner as molybdenum oxide-aluminum system.

During the combustion part of the material was expelled from the graphite channel. However, a significant part was collected after combustion was completed. The temperatures around  $3150^\circ\text{C}$  were recorded. The measured velocity of the combustion front propagation in air was  $0.523 \text{ m/s}$ . This velocity is significantly higher than that observed during titanium-boron reaction in argon (few centimeters per second). It was observed that a flame spreading on the surface being in contact with the surrounding air accelerates the reaction. Apparently, gas transport and oxidation reactions of both reactants are responsible for this acceleration.

A typical SHS cutting unit described above contains as a fuel different type of aluminothermic mixtures. These mixtures can achieve temperatures in the range  $2600\text{--}2800^\circ\text{C}$ . Our aim was to develop an energetic mixture, which could produce much higher combustion temperatures. A very promising system is a mixture of aluminum and iodine pentoxide. The iodine pentoxide was purchased from the Alfa Chemicals Company. The compound is hygroscopic and rather sticky when processed. Aluminum powder used in the experiments was Reynolds Al powder with average particle size of  $5\mu$ . Two different reactions were considered :



For densities  $\rho(\text{Al}) = 2.7 \text{ g/cm}^3$  and  $\rho(\text{I}_2\text{O}_5) = 4.98 \text{ g/cm}^3$  the heat generated by the second reaction is  $1,831.5 \text{ cal/g}$  and  $7,469.6 \text{ cal/cm}^3$ .

Thermodynamic calculations performed using HSC Chemistry Program (ver.5) have shown that both reactions are capable of generating very high adiabatic temperatures. The calculated temperatures were  $8383^\circ\text{C}$  and  $7716^\circ\text{C}$  for reactions

**Adiabatic Temperatures versus Dilution Percentages in Molybdenum Oxide System**  
 **$\text{MoO}_3 + 2\text{Al} \rightarrow \text{Al}_2\text{O}_3 + \text{Mo}$**

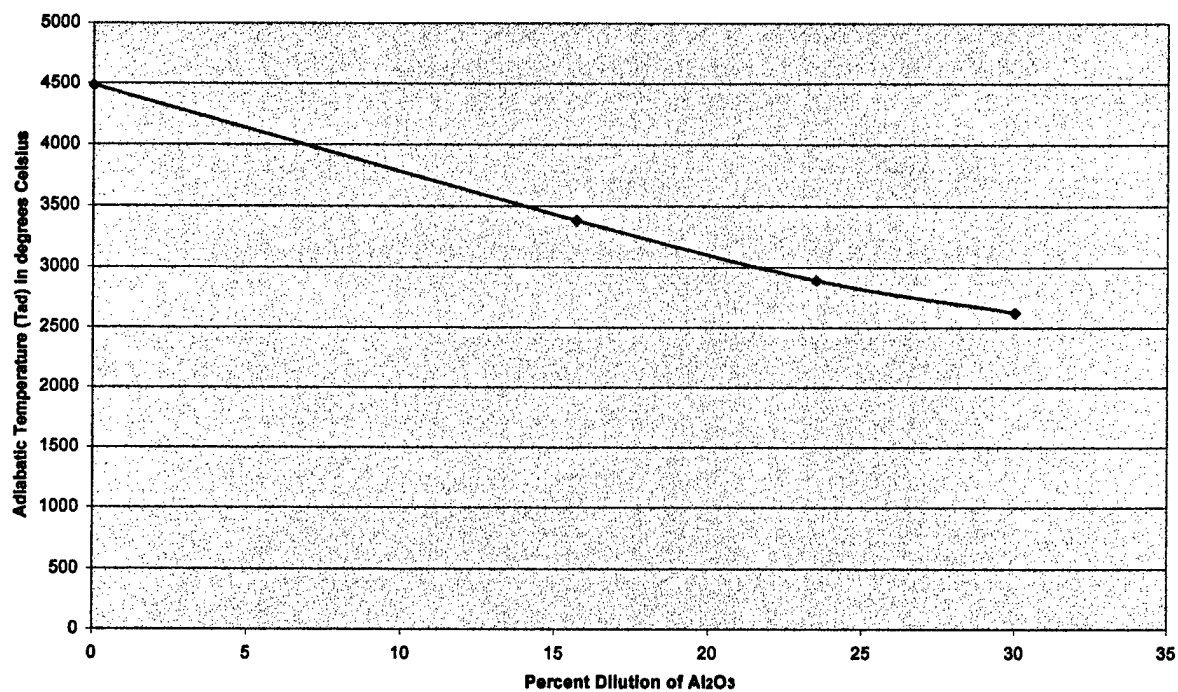


Figure 5. Adiabatic temperatures in  $\text{MoO}_3 - \text{Al}$  system

one and two, respectively. It should be noted that these estimates might not be very accurate due to significant error introduced by the extrapolation of thermodynamic properties. The available data are accurate to 4000 K.

Reactant mixture corresponding to the stoichiometry of the first reaction was prepared in a small quantity (2g batch). Both reactants were mixed by sieving them through mesh # 80. This operation was repeated ten times to ensure good mixing. The brass sieve was grounded and the personnel was protected by a complete fire suit and shielding made from ½ inch thick polycarbonate. Initially, 0.5 g of this mixture was ignited by using propane torch in order to determine the behavior of this system. The mixture ignited immediately on contact with flame. Strongly penetrating white flame was generated, significantly influencing eyesight. During the combustion a strongly purple smoke was released. A typical iodine odor was detected. Later two experiments with 15 and 30 grams were performed. The reaction was initiated using resistively heated molybdenum wire. The reaction was very violent. Large amount of violet smoke was generated upon ignition and extremely bright flame was produced. The temperature was so high that no solid residuum was found in the combustion unit. This is in accordance with thermodynamic calculations, which reveal that the products of the reaction (alumina!) are in the gaseous phase. The average velocity of the combustion, estimated from the thermal response of W-Rh thermocouples, was 4.5 m/sec.

To our knowledge this reaction is among the most exothermic known to us and the system is ideally suited for SHS cutter and solid detonation. More experiments must be performed in the Phase II. In particular slurry of aluminum powder and iodine pentoxide in gasoline is a promising material.

In a US Patent 4,216,721 the authors claim that it is possible to construct a thermal penetrator device, which takes advantage of steel plate penetration by liquid iron produced by aluminothermic reaction (20). We tried to repeat their experiment. Our results are reported below.

**The Iron Oxide – Aluminum – Iron System** consisted of a mixture of 15% by weight Fe as diluent,  $\text{Fe}_2\text{O}_3$ , ALCOA 123 aluminum ( $d_{\text{avg}}=18 \text{ :m}$ ) ; steel plate; clay crucible with the bottom removed, molybdenum ignition wire; gaseous oxygen; liquid oxygen; shielding and a variable voltage transformer. The clay crucible was placed on the steel plate where it was filled with 100 grams of the reactant mixture. A valley was then made in the middle of the mixture to where the steel plate could be seen. The molybdenum ignition wire was placed at the top of the iron mixture. The reaction was completed within a fraction of second. Both products, alumina and iron, were melted. No significant melting was observed on the steel plate.

Based on this experiment we can conclude that this technology is a very clumsy approach to attack steel plates. Our a priori theoretical analysis indicated that this

approach cannot compete with other technological methods of fast cutting and therefore we have not been surprised by negative experimental results.

### **III. 11. Combustion of iron plate in oxygen.**

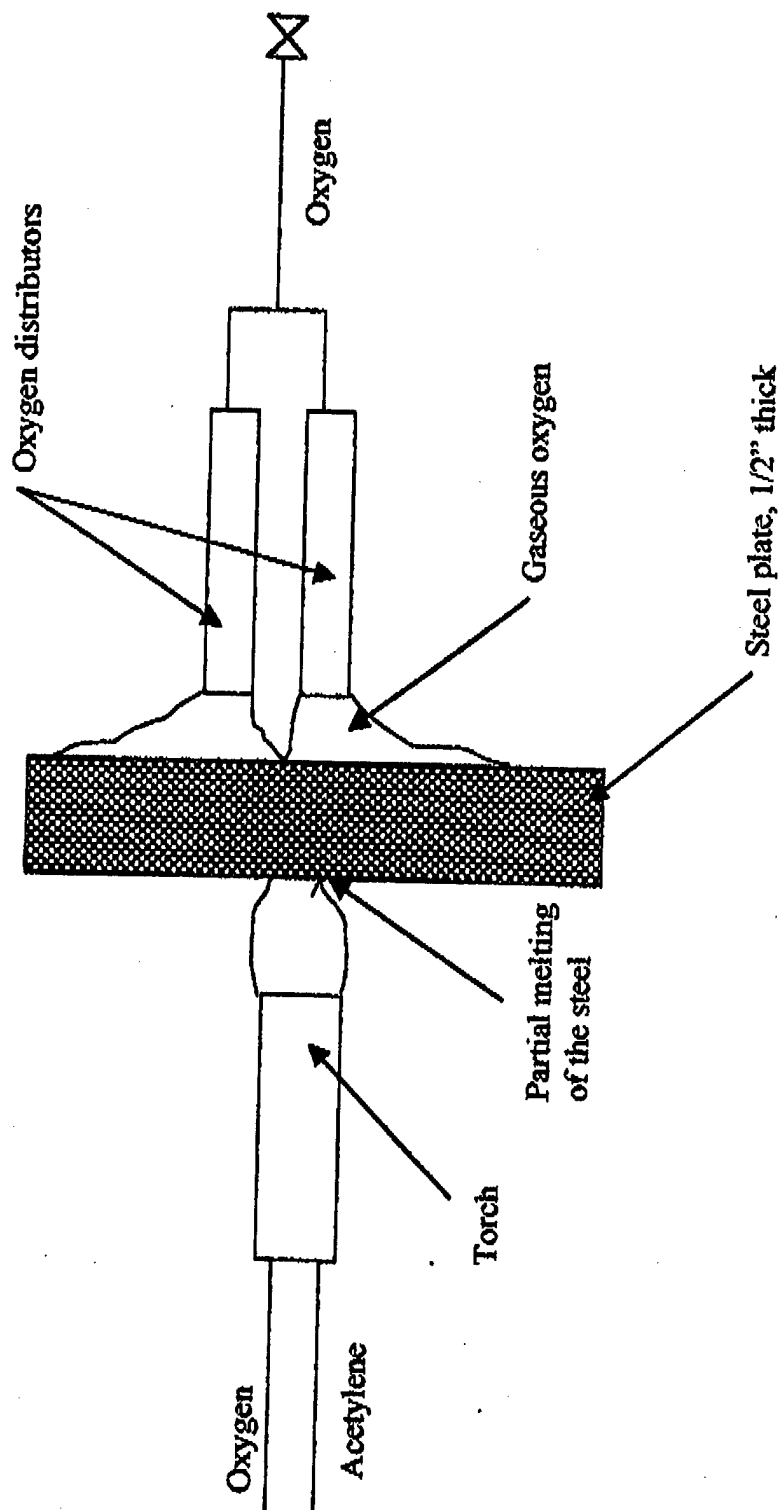
Two different types of experiments were performed to determine the reactivity of oxygen with hot steel. In the first series of experiments a  $\frac{1}{2}$ ' thick steel plate was mounted vertically (see Figure 4.6). Acetylene torch was placed on one side of the plate and oxygen distribution system on the other side. The plate was heated up to the melting point of steel (small hole approx.  $\frac{1}{4}$ " in diameter was generated on the oxygen side. The plate was red hot but no visible burning was observed when acetylene torch was removed. The visual observations indicated that the oxygen flow had no significant effect on self-sustaining character of the process and rather caused cooling of the plate.

The second type of experiments involved liquid oxygen. In this case, the plate was mounted horizontally. The acetylene torch was placed below the plate and liquid oxygen was poured on the plate when the temperature of the plate reached about  $1000^{\circ}\text{C}$ . Surface temperature of the plate was measure using optical pyrometer. The schematic of this experimental setup is shown in Figure 4.7. When liquid oxygen was poured directly on the upper side of the hot surface sudden evaporation process took place with a formation of small droplets escaping the surface due to their ejection by sudden evaporation. No visible effect of self-sustaining combustion process was observed. Again, when the acetylene torch was removed a fast cooling of the plate took place.

### **III.12. Carbochlorination of concrete sample.**

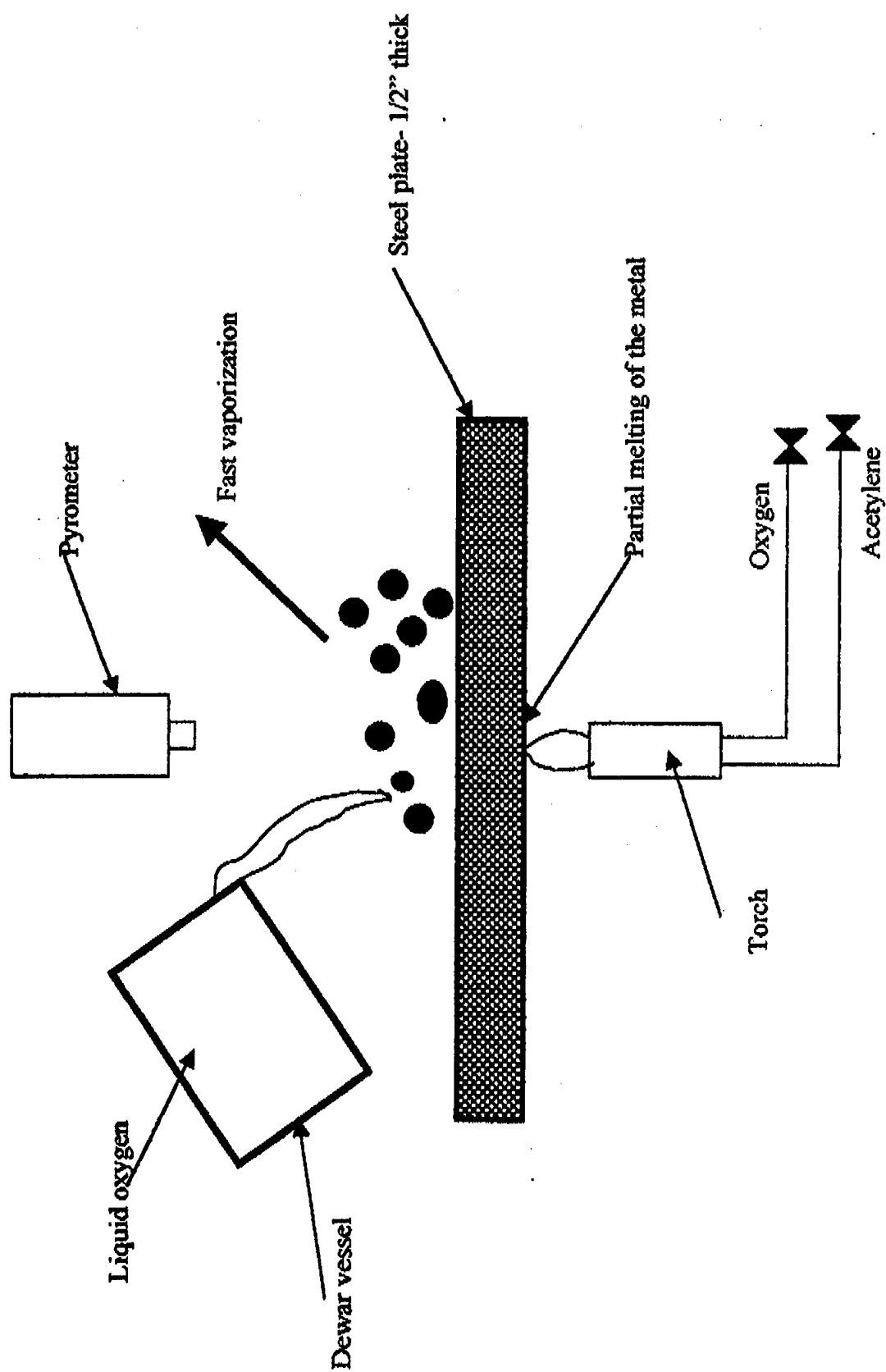
1. Concrete plate was crashed and sieved to -25 mesh and exposed to open air for 3 days.
2. Heating in furnace at  $1200^{\circ}\text{C}$  for 15 minutes with argon purging (200ml/min). removed 21% of volatile matter .
3. TG measurement: sample heated to  $1200^{\circ}\text{C}$  with heating rate of  $5^{\circ}\text{C}/\text{min}$  and air purging. The results are plotted in the attached figure, see Fig. 4.8. The figure reveals that at a  $900^{\circ}\text{C}$ , the volatile matter was completely removed.
4. Chlorination using chloroform: Sample of 2.3 grams was placed in a ceramic boat. Argon flow of 500 ml/min bubbles through the liquid chloroform carrying the chloroform vapor to the reactor. At  $1000^{\circ}\text{C}$ , after 10 minutes of chlorination, the mass of the sample increased by 17.70%. The sample after chlorination was in a powder form and could be easily removed from the

Fig. 4.6



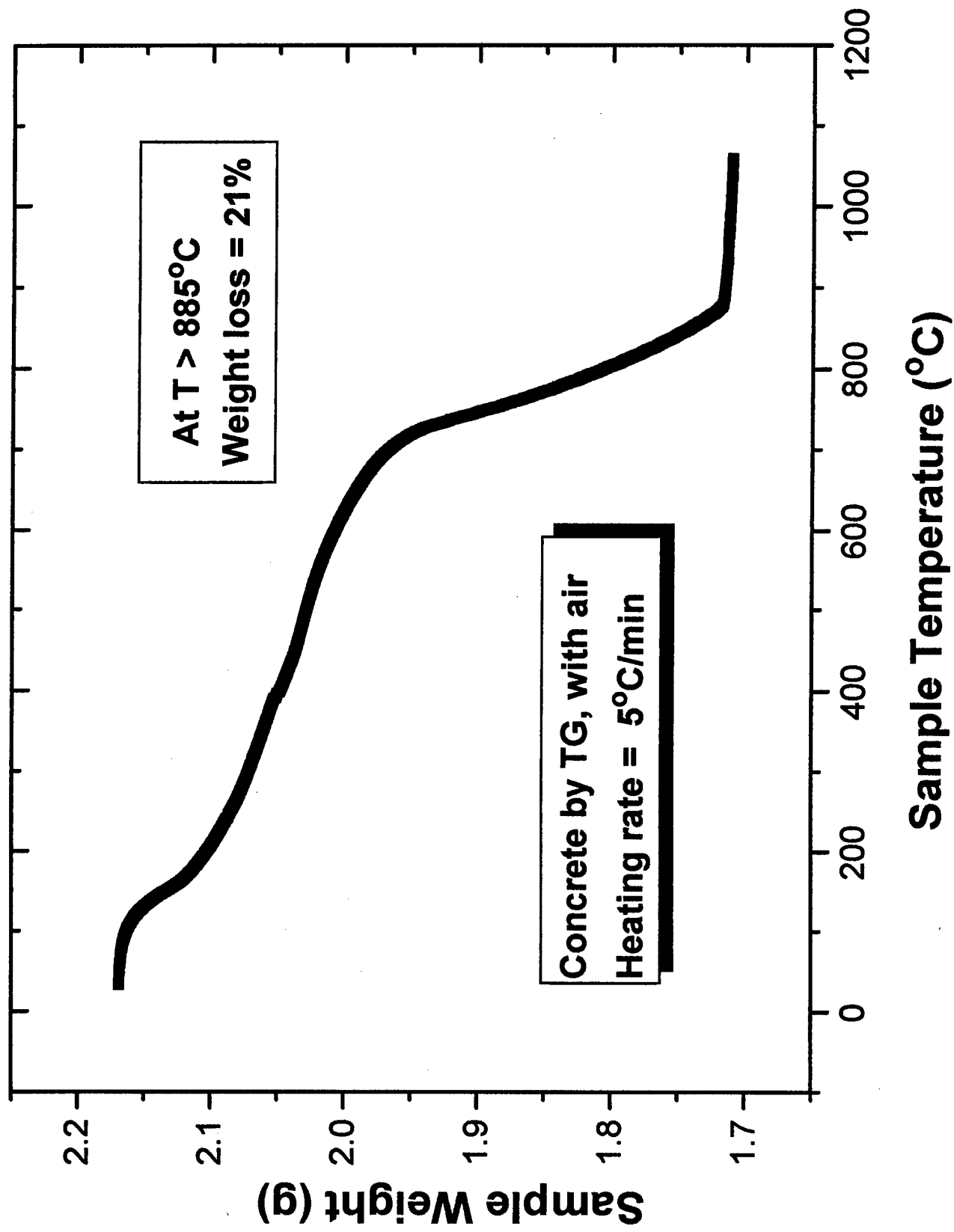
**Burning of steel in gaseous oxygen.**

Fig. 4.4



. Burning of steel in liquid oxygen.

Fig.4.8



ceramic boat. However, at 1200°C and after 10 minutes of chlorination, the sample melted and stuck to the ceramic boat.

**Table 1.**Chlorination of concrete by  $\text{CHCl}_3$ .  $T=1000^\circ\text{C}$ , residence time  $t=10$  min., argon flow-rate 500ml/min

Concrete sample –25 mesh	Sample #1	Sample #2
Sample mass, original (g)	2.3111	3.1468
Equivalent sample mass on a 1000°C dried base (g)	1.8258	2.4860
Sample mass after chlorination (g)	2.0639	2.9450
Sample mass after water wash and dried at 100°C (g)	1.4567	1.9160
Mass loss after chlorination (on a 1000°C dried base)	-17.70%	-18.46%
Conversion of concrete (on a 1000°C dried base)	20.22%	22.93%



Analysis and calculated conversion of each component contained in the cement sample(based on total conversion of 21.58%; 100 grams of original dry sample as calculation basis)

	Original sample on dry basis (g)	Sample chlorinated at 1000°C, 10 min by CHCl <sub>3</sub> and washed by warm water (g)	Conversion (%)
Al <sub>2</sub> O <sub>3</sub>	5.73	5.53	3.49
CaO	23.94	6.41	73.22
Cr <sub>2</sub> O <sub>3</sub>	0.01	0.01	0
Fe <sub>2</sub> O <sub>3</sub>	2.05	1.14	44.39
K <sub>2</sub> O	1.01	0.38	62.38
MgO	5.89	5.33	9.51
MnO	0.06	0.02	66.67
Na <sub>2</sub> O	0.86	0.49	43.02
P <sub>2</sub> O <sub>5</sub>	0.09	0.06	33.33
SiO <sub>2</sub>	60.09	58.76	2.21
TiO <sub>2</sub>	0.28	0.25	10.71

The results of this experiment indicate that calcium oxide can be converted easily under these conditions to chloride while silica remained in the original form. The conclusion from this experiment reveals that the concrete sample cannot be completely converted to chlorides at 1000°C. Of course, in a cutting flame the temperature is much higher and silica can be also converted. More experiments in the Phase II must be carried out to verify the concept of cutting concrete under carbochlorination conditions.

### **III.13. Systematic literature search.**

We have carried a systematic literature search using Chemical Abstract, Patent Gazette, Internet and Thomas Register. We have located more than 200 relevant references which are on our file as hard copies. In particular we paid attention to German and Russian literature.

### **IV. Conclusions and recommendations**

The information presented in this 1<sup>st</sup> Phase SBIR report reveals that defeating exposed rebar, steel reinforced concrete walls, steel-encased concrete doors, and steel plate doors is within reach of current technologies. We did not analyze any exotic solutions that may be very high risk or users unfriendly, but proposed to use or modify current technologies through clever engineering.

In particular we addressed in this report portable unit aspects. Under portable units we understand cutting systems, which can be easily transported by a team of two infantrymen without support of 4WD vehicles. We will refer to units, which can be transported on planes and locally transported on 4WD vehicles as Hammer "small cutting units". Both portable and small units can be very important for Special Forces in urban warfare, anti-terrorist actions and other operations.

Oxyfuel unit including 0.5-gallon gasoline tank with cutting torch assembly and 8 small cylinders of oxygen represents a typical portable unit. The overall weight of this package is 140 lbs. A team of two men can transport this package. The capability of this package is cutting 400 rebars  $\frac{1}{2}$  inch thick or making a cut 180 inches long on a plate 2.64 inches thick. A simple analysis reveals that the "quantity of work determining step" is amount of oxygen available. For effectiveness of such a team liquid oxygen is evidently a final solution. Remember that liquid oxygen is 800 times denser than gaseous oxygen. The research work on efficiency and cutting speed with liquid oxygen should be done in the Phase II.

According to our preliminary estimates a small cutting system package, transported by one 4WD vehicle, which includes gasoline tank containing 5 gallon gasoline, two cutting torches assembly and one tank of liquid oxygen (200lbs) can increase the capability of portable unit by factor 20 and more. The weight of this package will be less than 300 lbs.

A typical portable cutting unit based on the thermal lance concept has an overall weight 20 lbs., this includes handle and burning bar (3lbs) and small oxygen tank (16lbs). Oxygen consumption is typically 4 ft<sup>3</sup>/min. A small gas cylinder can support 4 min. cutting operation. On the other hand a small unit containing liquid oxygen tank can support the cutting operation for almost 700 min. Evidently both

oxyfuel and thermal lance small package outfit can achieve unbelievable cutting performance.

Operation with liquid gases is safe and liquid oxygen cutting technology has been done very recently used by a German metallurgical firm to cut large ingots. They reported a cutting speed increase by factor more than two; this factor was omitted in the considerations above therefore we must consider our estimates of cutting with liquid oxygen very conservative. Liquid gases can be transported easily and good insulation can keep the gases in liquid state for several days to weeks.

In our future work we are contemplating to design and test two packages, which can produce oxygen on the spot. One principle is using pressure swing adsorption; bench scale units, developed for hospitals, are available. These units produce oxygen of 97% purity. This oxygen is not pure enough for our cutting purposes and therefore we must modify the portable unit to be capable of delivering 99.2% oxygen.

Very efficient method of generating 100% pure oxygen is electrolysis of water. A portable system is available. This system can be driven by an electrical generator, which can be driven by a Diesel engine. We are convinced that the entire unit can be easily placed on a 4WD vehicle.

Both of these systems can be considered as auxiliary units for Special Forces if the time schedule will not allow getting oxygen from commercial suppliers in the country. We plan to design these systems in such a way that after short period of time after landing they will provide enough oxygen to start a cutting operation. These systems will be also very useful in military hospitals and in civilian sectors they can be used when disasters struck (derailment, earthquake etc.)

We can also generate oxygen from solid sources in a similar way as airline use in emergency. This process is based on thermal decomposition of chlorates. Typical system commercially available does not produce enough oxygen flow and in future we must design a chemical reactor for producing at least 20 ft<sup>3</sup>/min. of oxygen.

Our experience with cutting reinforced concrete indicates that this is a slow process because of high viscosity of produced lava. Cutting the concrete plates by thermal lance in closed rooms will produce a lot of smoke and the environment will require a gas mask for the operators. It seems to us that the fastest way of overcoming reinforced massive concrete plates is a combined two-stage technology. In the first stage the operator will pulverize the concrete by high velocity impact of a flying plate; a portable oxyfuel unit can eliminate the remaining twisted structure of rebars.

## V. References.

1. Eager Thomas W.; "Energy Sources Used for Fusion Welding", in Welding Encyclopedia.
2. Oreper G. M. and Szekely J., "Heat and Fluid Flow Phenomena in Weld Pools", Jour. Of Fluid Mechanics, Vol.98, 787 (1984)
3. Cassel H. M. et al., 3rd Symposium on Combustion, Baltimore, 185-190 (1949)
4. Goroshin S. et al., Burning Velocities in Fuel-Rich Aluminum Dust Clouds, 26<sup>th</sup> International Symposium on Combustion (Naples, Italy, 1996)
5. Martin J. and Murray S., Metastable Interstitial Compounds, Los Alamos Memo (August 12, 1997)
6. Fischer S.H. and Grubelich M.C., A Survey of Combustible Metals, Thermites and Intermetallics for Pyrotechnic Applications; 32<sup>nd</sup> AIAA/ASME/SAE/ASEE Joint propulsion Conference, Lake Buena Vista, Fl, July 1-3, 1996.
7. Yagodnikov D. A., et al., Enhancing the Propagation velocity of a Flame Front in an Aluminum Aerosuspension; Fizika Gorenija i Vzryva, Vol. 28, 2, 51-54 (1992), in Russian
8. Sweetman W. G., Chemical Cutting Method and Apparatus for Use in Wells, US Patent # 3,076,507 (Feb. 5, 1963)
9. Aslamov S. K. et al., Oscillatory Combustion of Air Suspensions, Fizika Gorenija i Vzryva, Vol. 29, 2, 36-43 (1992), in Russian
10. Efimov B. G. et al., Effect of Air Flow on Titanium Plate Combustion, Fizika Gornija i Vzryva, Vol. 25, 29-34 (1989), in Russian
11. Efimov B. G. and Zaklayzinskii L.A., Initiation of Combustion of Titanium Plates in an Air Stream by Pulsed Radiation, Combustion, Explosion and Shock Waves, Vol. 30, 178-181 (1994)
12. Scale-down of Chemical Reactors, Plenary lecture at AIChE Meeting, Nov. 1997, Los Angeles.
13. Clark A. F. et al., Combustion of Bulk Titanium in Oxygen, 15<sup>th</sup> Symposium on Combustion, 489-499 (1974)
14. Kuo K.K., Combustion of Massive Steel Plate in Liquid Oxygen, unpublished observation (Penn State Univ., Dec. 1998)
15. Hlavacek V., Combustion of Tantalum Powder in Liquid Nitrogen, unpublished observation (SUNY/Buffalo, 1989)
16. Rozner A.G., Pyronol Torch for Cutting Metals, Internal Report, NSWC, Indian Head, MD (1981)
17. Helms H.H. and Rozner A.G., US Patent # 3,695,951 (1972)
18. Heymann F.J., High Speed Impact Between a Liquid Drop and a Solid Surface, Jour. Appl. Physics, Vol.40, 5113-5122 (1969)

19. Bowden F.P. and Brunton J.H., The Deformation of Solids by Liquid Impact Solid Impact and by Supersonic Speeds, Proc. Royal Society, London A 263, 433-450 (1961)
20. Marziano S.J. and Donnard R.E., Thermite Penetration Device, US Patent # 4,216,721 (Aug. 12, 1980)
21. Balankin A.S., Physics of Penetration of a Cumulative Jet into Porous Media, Combustion, Explosion and Shock Waves Vol.25, 130-140 (1989)
22. Gotzmer C., Cutting of Metallic and Ceramic Plates, Personal communication, Navy Surface Warfare Center ,Indian Head ,MD (January 1996)
23. Hlavacek V., Cutting of Concrete Blocks, unpublished observations (1998)
24. Yang Fenglin and Hlavacek V., Kinetic Study of Chlorination of Niobium (V) Oxide with Chlorine and Carbon Monoxide, Powder Technology, in press.
25. White Paper on "Creation of Man Size Holes in Steel Reinforced Walls and Doors by Thermal Methods" (Joint DOD/DOE Reactive Materials Committee, July 1997)
26. Gatica J.E. and Hlavacek V., Laboratory for Ceramic and Reaction Engineering, Ceramic Bulletin, Vol. 69,No.8 (1990)

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